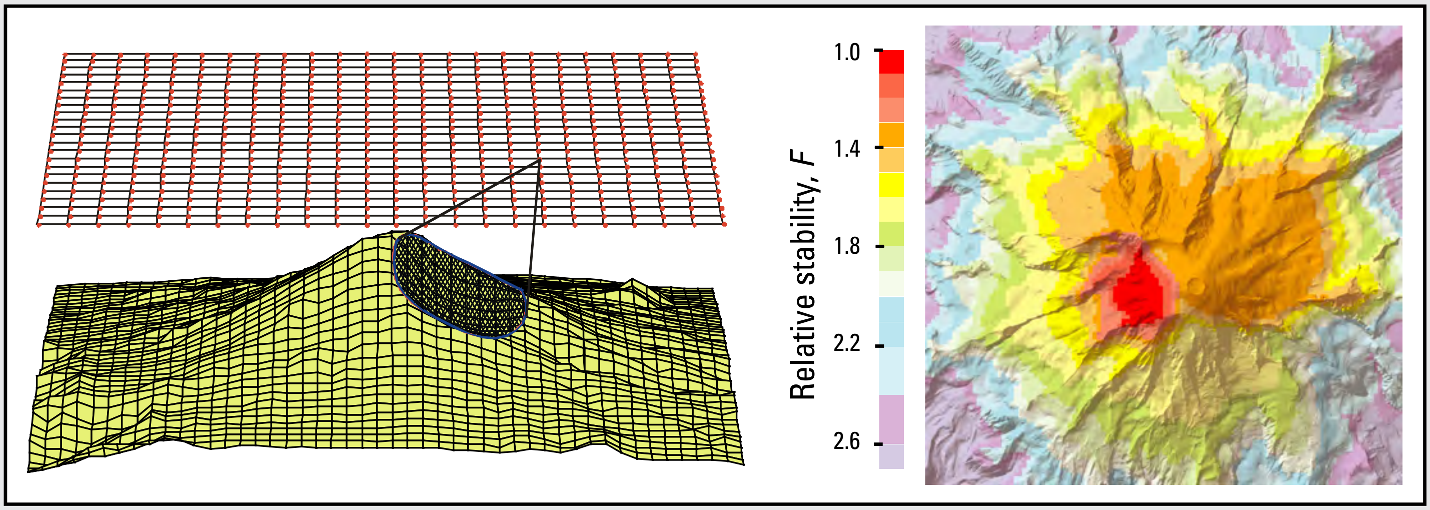
Scoops3D—Software to Analyze Three-Dimensional Slope Stability Throughout a Digital Landscape

Chapter 1 of
Section A, Modeling Methods
Book 14, Landslide and Debris-Flow Assessment



Techniques and Methods 14–A1

U.S. Department of the Interior
U.S. Geological Survey

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By Mark E. Reid, Sarah B. Christian, Dianne L. Brien, and Scott T. Henderson

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Notation

(L=length, M=mass, T=time)

$a_{i,j}$	length of the moment arm for the *i,j* column in a potential failure mass, relative to the axis of rotation, (L)
a_{FX}	one of the parameters describing the shape of the Fredlund and Xing (1994) soil-water characteristic curve, ($ML^{-1}T^{-2}$)
A	total area of a trial slip surface, (L^2)
A_c	total area of the trial slip surface for a column in a potential failure mass, (L^2)
A_h	horizontal area of a trial slip surface, (L^2)
$A_{h_{i,j}}$	horizontal area of the trial slip surface for the *i,j* column in a potential failure mass, (L^2)
$A_{i,j}$	area of the trial slip surface for the *i,j* column in a potential failure mass, (L^2)
c	cohesion of an earth material, ($ML^{-1}T^{-2}$)
$c_{i,j}$	cohesion on the trial slip surface for the *i,j* column in a potential failure mass, ($ML^{-1}T^{-2}$)
$C(\psi)$	correction factor for Fredlund and Xing (1994) soil-water characteristic curve

cellsize — length of one side of a square Esri ASCII raster grid cell in a digital elevation model (DEM), equal to Δx and Δy, (L)

$e_{i,j}$ — length of horizontal driving force moment arm for the *i*,*j* column in a potential failure mass, relative to the axis of rotation, used for pseudo-static analysis of earthquake loading, (L)

F — factor of safety, (dimensionless)

F_i — initial estimate of factor of safety, used in Bishop's simplified method of analysis, (dimensionless)

F_{min} — minimum factor of safety computed during the current search, (dimensionless)

F_{new} — current factor of safety computed during the iterative process in Bishop's simplified method of analysis, (dimensionless)

F_{old} — previous factor of safety computed during the iterative process in Bishop's simplified method of analysis, (dimensionless)

F_O — factor of safety found using the Ordinary (Fellenius) method of analysis, (dimensionless)

F_{rel} — relative factor of safety defined as F / F_{min} , (dimensionless)

g — magnitude of gravitational acceleration, (LT^{-2})

h — pore-water (or fluid) pressure head, (L)

H — height of hillslope or embankment, (L)

i — integer counter for location of search-lattice node, grid cell, or 3D data in the x-direction, (dimensionless)

j — integer counter for location of search-lattice node, grid cell, or 3D data in the y-direction, (dimensionless)

k — integer counter for location of search-lattice node or 3D data in the z-direction, (dimensionless)

k_{eq} — horizontal pseudo-acceleration coefficient for earthquake loading, expressed as a fraction of *g*, (dimensionless)

m_α — term for part of the computation of normal force acting on a trial slip surface, used in Bishop's simplified method of analysis, (dimensionless)

$m_{\alpha_{i,j}}$ — term for part of the computation of normal force acting on the trial slip surface of the *i*,*j* column in a potential failure mass, used in Bishop's simplified method of analysis, (dimensionless)

m_{FX} — one of the parameters describing the shape of the Fredlund and Xing (1994) soil-water characteristic curve, (dimensionless)

M_d — driving moment of a potential failure mass around axis of rotation, (ML^2T^{-2})

$M_{d,earthquake}$ — driving moment due to horizontal force from earthquake loading, (ML^2T^{-2})

$M_{d,gravity}$ — driving moment due to weight of potential failure mass, (ML^2T^{-2})

M_r — resisting moment of a potential failure mass around axis of rotation, (ML^2T^{-2})

n_{FX} — one of the parameters describing the shape of the Fredlund and Xing (1994) soil-water characteristic curve, (dimensionless)

n_{vG} — one of the parameters describing the shape of the van Genuchten (1980) soil-water characteristic curve, a measure of the soil pore-size distribution, (dimensionless)

$N_{i,j}$ — normal force acting on the trial slip surface of the *i*,*j* column in a potential failure mass, equal to $\sigma_{n_{i,j}} A_{i,j}$, (MLT^{-2})

r_u	pore-pressure ratio, defined as ratio of pore pressure to total vertical stress, (dimensionless)
R	radius of a sphere containing a trial slip surface, (L)
$R_{i,j}$	distance from the axis of rotation to the center of trial slip area for the *i*,*j* column in a trial failure mass, (L)
s	shear strength, or mobilized shear resistance, of an earth material, ($ML^{-1}T^{-2}$)
$s_{i,j}$	mobilized shear strength for the basal slip surface of the *i*,*j* column in a potential failure mass, ($ML^{-1}T^{-2}$)
S_e	effective degree of saturation of an earth material, used for estimating suction-stress effects, (dimensionless)
$S_{i,j}$	resisting shear force acting against slip on the trial slip surface of the *i*,*j* column in a potential failure mass, (MLT^{-2})
S_0, S_2	surface areas of the two parallel sides of a partial column above the trial slip surface in a potential failure mass, (L^2)
S_1	surface area of a vertical cross section through the middle of a partial column above the trial slip surface in a potential failure mass, (L^2)
T	average resisting shear force at equilibrium over a trial slip surface, ($ML\,T^{-2}$)
u	pore-water pressure, negative values denote matric suction, ($ML^{-1}T^{-2}$)
V_c	volume of each column (partial or full) above a trial slip surface, (L^3)
W_c	weight of a column in a potential failure mass, (MLT^{-2})
$W_{i,j}$	weight of the *i*,*j* column in a potential failure mass, (MLT^{-2})
x, y	horizontal orthogonal coordinates, (L)
xllcorner	spatial coordinate in the x-direction of the lower left (southwest) corner of an Esri ASCII raster grid, such as a digital elevation model (DEM), (L)
yllcorner	spatial coordinate in the y-direction of the lower left (southwest) corner of an Esri ASCII raster grid, such as a digital elevation model (DEM), (L)
z	vertical coordinate, (L)
z_{pz}	vertical depth beneath a piezometric surface, (L)
α	local apparent dip angle in the direction of slip on a trial surface, (º)
$\alpha_{i,j}$	apparent dip of the column base in the direction of slip for the *i*,*j* column in a potential failure mass, (º)
α_m	local apparent dip angle in the direction of slip on a trial surface for the column in a potential failure mass with the maximum negative θ value, used for computing $ß_{3D}$ when there are negative θ values, (º)
α_{vG}	one of the parameters describing the shape of the van Genuchten (1980) soil-water characteristic curve, related to the inverse of the air entry suction, (LT^2M^{-1})
$ß_{3D}$	quantity used for estimating initial factor of safety, F_i, in Bishop's simplified method of analysis, (dimensionless)
δ	azimuthal angle of the slip movement direction, measured counterclockwise from zero in the positive x direction, (º)

ε	local dip angle on trial slip surface, positive in the direction of sliding, (º)
$\varepsilon_{i,j}$	dip direction on the trial slip surface for the *i*,*j* column in a potential failure mass, (º)
ε_m	dip angle on trial slip surface for the column in a potential failure mass with the maximum negative ε value, used for computing $ß_{3D}$ when negative ε values occur, (º)
ϕ	angle of internal friction of an earth material, (º)
$\phi_{i,j}$	angle of internal friction on trial slip surface for the *i*,*j* column in a potential failure mass, (º)
ϕ_m	angle of internal friction on trial slip surface for the column in a potential failure mass with the maximum negative θ value, used for computing $ß_{3D}$ when there are negative θ values, (º)
γ	unit or specific weight of an earth material, weight per unit volume, $(ML^{-2}T^{-2})$
γ_d	unit weight of a dry earth material, weight per unit volume, $(ML^{-2}T^{-2})$
γ_{ps}	unit weight of a partially saturated earth material, weight per unit volume, $(ML^{-2}T^{-2})$
γ_s	unit weight of a saturated earth material, weight per unit volume, $(ML^{-2}T^{-2})$
γ_t	total unit weight (solid plus fluid) of an earth material, weight per unit volume, $(ML^{-2}T^{-2})$
γ_w	unit weight of pore water (or pore fluid), weight per unit volume, $(ML^{-2}T^{-2})$
λ	ratio of cohesive to frictional material strength, defined as $c / \gamma H \tan\phi$, (dimensionless)
θ	volumetric water content of an earth material, (dimensionless)
θ_r	residual volumetric water content of an earth material, (dimensionless)
θ_s	saturated volumetric water content of an earth material, (dimensionless)
σ_n	normal stress acting on a trial slip surface, $(ML^{-1}T^{-2})$
$\sigma_{n_{i,j}}$	normal stress acting on the trial slip surface for the *i*,*j* column in a potential failure mass, $(ML^{-1}T^{-2})$
τ	shear stress required to maintain equilibrium along a trial slip surface, $(ML^{-1}T^{-2})$
ψ	matric suction, note that suction is negative pore pressure relative to atmospheric pressure, $(ML^{-1}T^{-2})$
ψ_r	residual matric suction, note that suction is negative pore pressure relative to atmospheric pressure, $(ML^{-1}T^{-2})$

Scoops3D: Software to Analyze Three-Dimensional Slope Stability Throughout a Digital Landscape

By Mark E. Reid, Sarah B. Christian, Dianne L. Brien, and Scott T. Henderson

Abstract

The computer program, Scoops3D, evaluates slope stability throughout a digital landscape represented by a digital elevation model (DEM). The program uses a three-dimensional (3D) method of columns approach to assess the stability of many (typically millions) potential landslides within a user-defined size range. For each potential landslide (or failure), Scoops3D assesses the stability of a rotational, spherical slip surface encompassing many DEM cells using a 3D version of either Bishop's simplified method or the Ordinary (Fellenius) method of limit-equilibrium analysis. Scoops3D has several options for the user to systematically and efficiently search throughout an entire DEM, thereby incorporating the effects of complex surface topography. In a thorough search, each DEM cell is included in multiple potential failures, and Scoops3D records the lowest stability (factor of safety) for each DEM cell, as well as the size (volume or area) associated with each of these potential landslides. It also determines the least-stable potential failure for the entire DEM. The user has a variety of options for building a 3D domain, including layers or full 3D distributions of strength and pore-water pressures, simplistic earthquake loading, and unsaturated suction conditions. Results from Scoops3D can be readily incorporated into a geographic information system (GIS) or other visualization software. This manual includes information on the theoretical basis for the slope-stability analysis, requirements for constructing and searching a 3D domain, a detailed operational guide (including step-by-step instructions for using the graphical user interface [GUI] software, Scoops3D-i) and input/output file specifications, practical considerations for conducting an analysis, results of verification tests, and multiple examples illustrating the capabilities of Scoops3D. Easy-to-use software installation packages are available for the Windows or Macintosh operating systems; these packages install the compiled Scoops3D program, the GUI (Scoops3D-i), and associated documentation. Several Scoops3D examples, including all input and output files, are available as well. The source code is written in the Fortran 90 language and can be compiled to run on any computer operating system with an appropriate compiler.

Chapter 1. Introduction

1.1. Purpose and Scope

Scoops3D is a computer program, developed by the U.S. Geological Survey (USGS), for analyzing slope stability throughout a digital landscape, as represented by a digital elevation model or DEM. It can systematically search a digital landscape and compute the stability of millions of three-dimensional (3D) potential landslides encompassing a wide range of depths and volumes that potentially affect different parts of the DEM. After this search, every DEM cell (except for those at the edges of the DEM) will have been included in a number of potential slope failures (landslides). An example of one potential slip surface intersecting a DEM is shown in figure 1.1. Results from Scoops3D analyses show the minimum factor of safety (an indicator of stability) for the potential slip surfaces affecting each DEM cell throughout the landscape, as well as the volumes or areas associated with these potential slope failures. The results represent an amalgamation of the least-stable 3D potential slope failures (fig. 1.2). Scoops3D uses a 3D "method of columns" limit-equilibrium analysis to compute the stability of potential slope failures (landslides) with a spherical potential slip surface. The user selects the landslide size range (in either area or volume) of interest. Scoops3D has a wide variety of user options: it can incorporate complex topography, full 3D distributions of parameters, including subsurface material properties and pore-water pressures, and simplistic earthquake loading effects. Our approach was originally described in Reid and others (2000) and has been further developed as described in this manual.

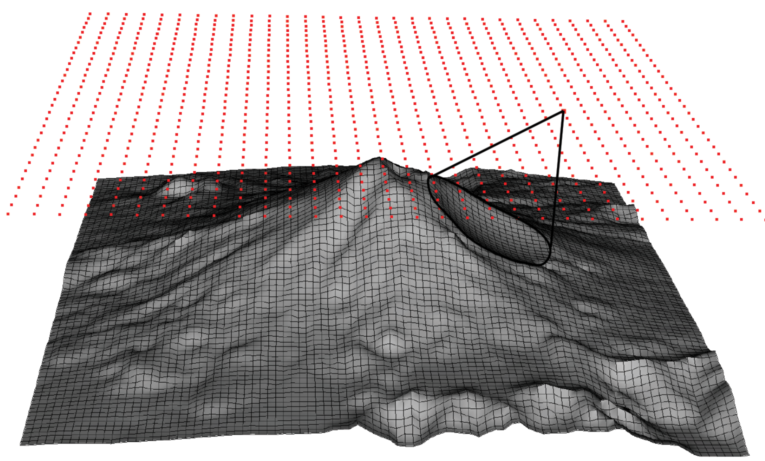

Figure 1.1. Perspective view of a digital elevation model (DEM) grid showing a potential failure with mass removed. The rotational center defining the spherical potential failure surface is a node above the DEM. Scoops3D uses a search lattice (one layer is shown) above the DEM to construct and analyze many different potential failures affecting all parts of the model.

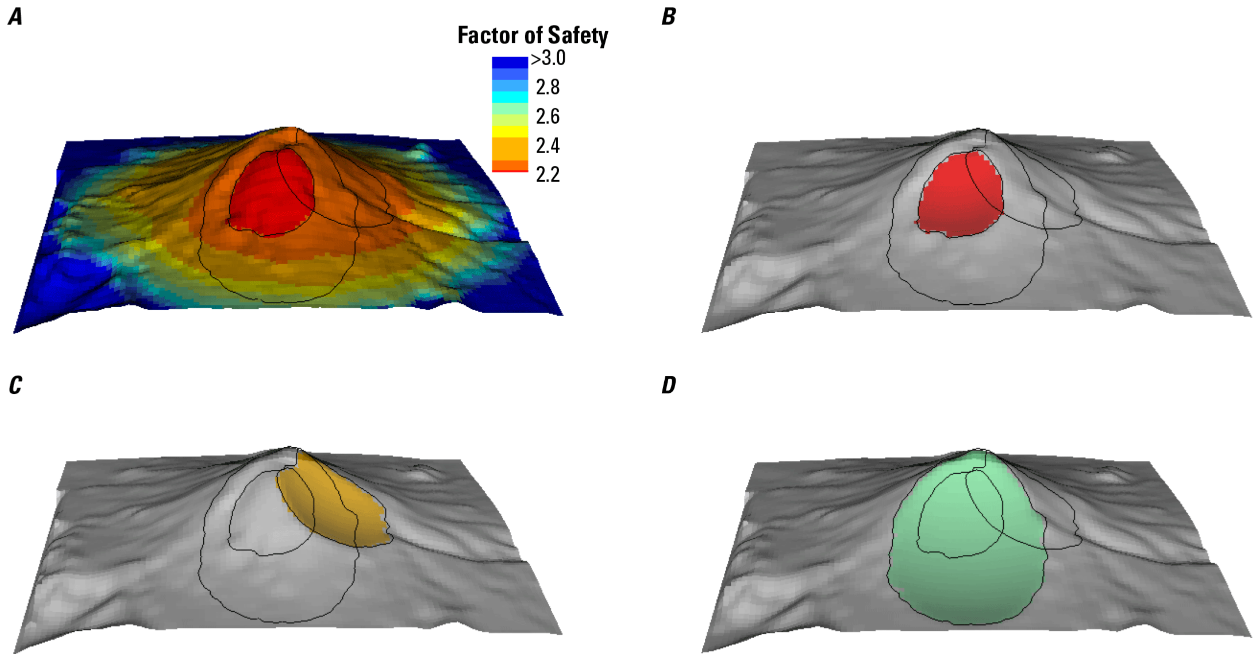

Figure 1.2. Four perspective views showing stability results from a Scoops3D analysis draped on digital topography and examples of three potential slip surfaces with potential failure masses removed. *A,* Lowest factor of safety found for each digital elevation model (DEM) cell. The results represent an amalgamation of the factors of safety computed for many potential slope failures. *B*, Potential slope failure with lowest factor of safety for entire DEM (global minimum). Slip surface shown in red with potential failure mass removed. *C* and *D*, Two other potential slope failures that are the least stable for select cells of the DEM. Note that the potential failures shown in *B*, *C*, and *D* overlap, but only the area encompassed by potential failure with the global minimum factor of safety (*B*) is portrayed in its entirety in *A*. The other two potential failures are only partially present in *A*; they are superseded in part by other potential failures with lower factors of safety.

Digital elevation representations of topography are readily available for many parts of the world, and Scoops3D uses a DEM as the foundation for its 3D slope-stability analysis. A number of other models use DEM topography to compute stability using a one-dimensional (1D) infinite slope analysis on a DEM cell-by-cell basis (Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Pack and others, 1998; Baum and others, 2010) or a two-dimensional (2D) stability analysis on a series of cross sections through a DEM (Miller, 1995; Miller and Sias, 1998). Some approaches use DEM topography in a Geographical Information System (GIS) framework to compute 3D stability (Xie and others, 2006a; Xie and others, 2006b). One- or two-dimensional computations of slope stability of uniform hillslopes are commonly more conservative (in other words, indicate lower stability) than 3D results (Cavounidis, 1987; Duncan, 1996), and therefore may be useful in engineering design. Nevertheless, there are several compelling reasons to use a 3D analysis to assess slope stability. Actual slope failures have an inherently 3D geometry, and a potentially more accurate 3D analysis can be advantageous for scientific inquiry or back analysis of an actual slope failure. Moreover, a 3D approach can integrate the effects of topography, strength, and pore pressures over potential failure areas larger than a single DEM cell. Lateral variation of these properties within a potential failure mass may significantly affect stability and thus render 1D and 2D computations inaccurate (Hungr, 1987; Stark and Eid, 1998; Bromhead and others, 2002). Furthermore, using 3D analysis provides direct estimates of potential failure volumes—a crucial element for many hazard assessments, sediment budgets, or initial conditions for landslide runout models.

We designed Scoops3D to address several problems. It can compute relative slope stability throughout a landscape using the best available information and thereby aid regional evaluations of landslide susceptibility or hazard. It can also be used as a screening tool to identify areas within the landscape having low stability that may warrant subsequent more detailed stability analysis. In addition, Scoops3D can be used to evaluate the differences in stability resulting from a series of plausible scenarios, such as effects of different 3D groundwater flow regimes or spatial variations in earth material properties.

Scoops3D has been used to assess the stability of volcano edifices at Mount Rainer in Washington State (Reid and others, 2001), Volcan Casita in Nicaragua (Vallance and others, 2004), Augustine Volcano in Alaska (Reid and others, 2010a), and pre-collapse Mount St. Helens (Reid and others, 2000; Reid and others, 2010b). It has also been coupled with a 3D regional groundwater flow model and used to analyze the stability of coastal bluffs in Seattle, Washington (Brien and Reid, 2007; 2008).

Scoops3D is written in the Fortran 90 language to enable fast computation and on-the-fly allocation of computer memory for variable problem sizes. This approach is more computationally efficient than directly performing calculations in a GIS framework. Compiled versions of the program run on a variety of computer operating systems, including Microsoft Windows, Apple Macintosh, and Linux. Our graphical user interface, Scoops3D-i, is written in the Python language and runs on either Windows or Macintosh systems; a compiled version of the interface is provided as part of the installation packages. The Scoops3D program, graphical user interface, user's manual, and associated example files are available for download over the Internet: http://pubs.usgs.gov/tm/14/a01.

This manual covers six areas in different chapters:

- Chapter 2 - the theoretical basis for the program (including limit-equilibrium analysis methods).
- Chapter 3 - requirements for building a 3D domain and searching the digital landscape.
- Chapter 4 - a detailed guide to program operation (including installing and running the program, using the graphical user interface [Scoops3D-i], creating input files, and selecting output options).
- Chapter 5 - practical considerations for performing and assessing the quality of a slope-stability analysis with Scoops3D.
- Chapter 6 - verification tests demonstrating the accuracy of the stability calculations obtained using Scoops3D.
- Chapter 7 - examples illustrating the features of Scoops3D.

1.2. Capabilities and Limitations

Scoops3D has the capability to determine the stability of all parts of a DEM; it does not just identify the potential failure with the overall lowest stability, as is common in many geotechnical approaches. This ability to thoroughly assess a DEM sets Scoops3D apart from most other 3D slope-stability models. Moreover, options in Scoops3D allow the user to easily perform multiple levels of analysis for different scenarios, such as determining the effects of topography alone and then adding detailed subsurface data as desired. The following list outlines some of the more significant capabilities and features of Scoops3D:

- Provides map view data of the minimum stability for potential failure surfaces affecting each DEM cell and can provide a 3D distribution of stability underlying the DEM.
- Provides volumes and (or) areas associated with the least-stable potential failure at each DEM cell.
- Searches for potential failures given user-defined size (area or volume) limits.
- Can compute the stability of potential failures sliding in any direction in the topography; slip directions do not need to be oriented with the axes of the DEM as required in many existing geotechnical software packages.
- Includes partial columns on the boundary of a potential failure mass, enabling more accurate results using coarser DEM resolutions and thereby reducing computer memory requirements.
- Incorporates coarse-to-fine search techniques to enhance computational efficiency; with these techniques, the time to search a DEM can be reduced by as much as 90 percent compared to a simple full search.
- Includes the option to represent subsurface material properties as layers in Esri ASCII raster format, allowing easy integration with Geographical Information System (GIS) software, such as Esri's ArcGIS. The ASCII format also allows creation of input files without needing a specific software package.
- Includes the option to represent subsurface materials by full 3D distributions of earth material strength and weight.
- Includes the option to simulate earthquake or seismic loading effects in a pseudo-static analysis.
- Includes options to represent pore-water pressure effects either with pore-pressure ratios (relative to vertical stresses), a piezometric surface, or a full 3D distribution of pressure heads. The effects of full 3D groundwater flow fields can be modeled by coupling results from separate groundwater flow models with Scoops3D.
- Includes the option to incorporate fully 3D variably saturated groundwater flow fields and the effects of unsaturated suction stresses.

As with all models, Scoops3D has limitations. Because Scoops3D uses conventional limit-equilibrium slope-stability approaches, it is subject to the well-known limitations of these approaches, such as the assumption of rigid failure masses with a uniform factor of safety along all sections of the pre-defined potential slip surfaces (Krahn, 2003; Duncan and Wright, 2005). In Scoops3D, potential failure surfaces are limited to a spherical representation undergoing rotational slip. This shape represents the simplest physically plausible 3D slip surface and proves useful for a broad assessment of a DEM; however, it may not be appropriate for precise evaluation of tabular, dominantly translational slides or more complex slip surfaces geometries. Stability is computed in Scoops3D using 3D extensions of either the Ordinary (Fellenius) or Bishop's simplified method. Neither of these methods, which are commonly used in geotechnical practice, computes a full 3D distribution of stresses within a hillslope, nor do they compute side forces between the columns in a potential failure mass. However, the 3D extension of Bishop's simplified method does typically provide factors of safety very close to more rigorous limit-equilibrium methods (Hungr, 1987; Ugai, 1988; Lam and Fredlund, 1993). Estimates of material deformation and strain, progressive failure, and dynamic loading may be better simulated using other geotechnical modeling approaches (Duncan, 1996; Duncan and Wright, 2005). Nevertheless, limit-equilibrium methods have been used for many years in engineering applications and have been calibrated by experience and observations (Krahn, 2003).

Scoops3D includes an option to analyze a single, specific potential failure surface, but does not include options to incorporate site-specific features such as tension cracks, external loads, non-linear strengths, partially submerged slopes, or complex failure-surface geometry. For most landscapes, it would be difficult to estimate the full 3D distribution of these site-specific features. Scoops3D does not require that potential failure surfaces exit or intersect a pre-defined point or layer. If any of these site-specific characteristics are important, then a stability analysis might be better performed using a commercially available 3D geotechnical slope-stability program such as CLARA-W (O. Hungr Geotechnical Research Inc., 2010), SVSlope (Fredlund and others, 2009), or TSLOPE (TAGA Engineering Software Services, 1984).

In contrast to site-specific engineering analyses, Scoops3D provides a tool to thoroughly assess the stability of an entire digital landscape. Interpretation of results from a Scoops3D analysis requires a complete understanding of the limits of the methods of stability analysis and the effects of the input data, particularly potential failure size limits, material strengths, and pore-water pressures. Although we have tested Scoops3D using a variety of published examples, users should take care to determine that Scoops3D is providing reasonable results for their applications. To aid in this determination, we suggest that users start their analyses with simple cases (such as the assumption of homogeneous properties) to first examine the effects of topography on stability and then progressively advance to more complicated scenarios. Practical considerations for performing and examining the quality of analyses are provided in chapter 5 of this manual.

Chapter 2. Basis of the Slope-Stability Analysis

Scoops3D calculates slope stability by extending conventional limit-equilibrium analysis to three dimensions (3D) using a method of columns. Many established and well-tested geotechnical analyses rely on limit-equilibrium methods to assess slope stability (Duncan, 1996; Duncan and Wright, 2005). Although 2D approaches are quite common, fewer applications of the method exist for 3D analysis. In this section, we describe our implementation of limit-equilibrium analysis for computing stability in a 3D domain.

Various 3D method-of-columns approaches have been described by other researchers (Hovland, 1977; Chen and Chameau, 1982; Hungr, 1987; Thomaz and Lovell, 1988; Ugai, 1988; Xing, 1988; Hungr and others, 1989; Lam and Fredlund, 1993; Okimura, 1994; Yamagami and Jiang, 1997; Huang and Tsai, 2000; Huang and others, 2002; Chen and others, 2003; Xie and others, 2003a,b; Jiang and Yamagami, 2004; Xie and others, 2006a; Cheng and Yip, 2007). Such methods rely solely on assessing the static equilibrium (moments and [or] forces) of a predefined potential failure mass; they assume a priori both the geometry of the potential failure and its mode of failure (for example, rotational or translational sliding). Limit-equilibrium analyses, including those used in Scoops3D, do not determine the strains and (or) displacements affecting the potential failure mass. The predefined potential failure or slip surface is termed the ***trial surface***[1]. Scoops3D uses trial surfaces composed of parts of a sphere and assumes rotational slip. A spherical trial surface represents the simplest 3D geometry unconstrained by internal structures, making it useful for regional stability analyses in which millions of trial surfaces may be examined in a DEM. A spherical arcuate surface has no sharp disruptions and forms a physically plausible potential shear surface. In materials without large contrasts or discontinuities in strength, failures are commonly arcuate (Hoek and Bray, 1981).

Limit-equilibrium methods typically divide the potential failure mass into sections (vertical slices in 2D and vertical columns in 3D) so that shear resistance on the trial surface can be estimated for each section. Shear resistance (strength) provided by friction is a function of the normal stress acting on a trial surface (see section 2.2). The 3D methods estimate normal stresses (or forces) at the base of each column where it intersects the trial surface; each column is assumed to be a rigid mass undergoing no internal deformation. Although dividing a potential failure mass into columns solves the issue of estimating normal forces on a curved trial surface, it leads to a statically indeterminate problem, in that some of the forces acting on the columns (such as normal and shear forces acting on the sides) are unknown. Thus, determining the forces acting on the trial surface of each column requires some assumptions about the side forces acting between columns. In this sense, the method is quasi-3D; it does not compute a full 3D stress field. Assumptions used to estimate side forces, and thus the basal normal forces acting on each section of a potential failure surface, constitute one of the primary distinguishing characteristics between different limit-equilibrium methods (for example, Duncan and Wright, 2005).

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[1]Terms in ***bold italic*** are defined in section, "Glossary of Selected Terms."

Limit-equilibrium methods assume failure occurs simultaneously along the trial slip surface, with no progressive failure. This implies that the factor of safety against sliding, *F*, is uniform everywhere along the trial slip surface and the forces computed for each section (column) are based on this assumption. Although these methods may lead to unrealistic local stresses on individual sections of the slip surface (Krahn, 2003), the global integration of all forces acting on the trial slip surface typically provides physically plausible values of *F*.

Scoops3D allows the user to select between two well-known geotechnical moment equilibrium methods to compute the stability of a rotational trial surface: the Ordinary (Fellenius) method and Bishop's simplified method (for example, Duncan and Wright, 2005). The two methods are computationally efficient and work well with 3D columns defined by a DEM. Both compute stability using moment equilibrium around an axis of rotation. Neither requires the computation of side forces acting between columns, and thus they avoid difficulties associated with computing side forces on column faces that are not aligned with the DEM grid (for example, Yamagami and Jiang, 1997). The methods differ primarily in how they estimate the normal force acting on the trial surface (see sections 2.3.1 and 2.3.2).

Each method has advantages and disadvantages. The Ordinary (Fellenius) method always provides a factor-of-safety value for a given rotational trial surface. It does not require an iterative process to find a factor of safety and this speeds computation. Factor-of-safety values computed using the Ordinary method in 3D are commonly slightly lower (more conservative) than those determined by other limit-equilibrium methods (Ugai, 1988; Lam and Fredlund, 1993) and this pattern tends to occur using Scoops3D as well. Although other investigators have shown that computed *F* values using the traditional Ordinary method in 2D can be unrealistically low if high pore-water pressures are present on the trial surface (Whitman and Bailey, 1967; Duncan and Wright, 1980, 2005), Scoops3D implements a slightly modified version of the Ordinary method (Lei and others, 2011) that provides more accurate *F* values with high pore pressures (see section 2.3.1).

In comparison, Bishop's simplified method provides factor-of-safety values similar to those found with more rigorous stability methods (such as the Spencer or Morgenstern-Price methods) in both 2D (Fredlund and Krahn, 1977; Duncan and Wright, 1980) and 3D (Hungr, 1987; Ugai, 1988; Lam and Fredlund, 1993). Bishop's simplified method requires an iterative solution method to compute *F*, and the iteration process occasionally fails to converge on a solution or converges on a spurious (that is, incorrect) solution – particularly if the trial surface includes very steep slip sections or is affected by high pore-water pressures. Scoops3D allows the user to filter spurious solutions. In general, we recommend selecting Bishop's simplified method because it provides more accurate solutions of *F*. If the user elects to use Bishop's simplified method, Scoops3D will also automatically compute values using the Ordinary method for comparison.

The following sections in this chapter present more details about how Scoops3D analyzes slope stability, including:

- Defining a potential 3D failure mass, slip direction, and weight distribution.
- Defining shear strength acting on the potential failure surface.
- General issues with computing 3D slope stability using a moment equilibrium analysis.
- Detailed descriptions of both the Ordinary (Fellenius) and Bishop's simplified methods extended to 3D.
- Incorporation of different pore-water pressure distributions and special cases.
- Slope-stability calculations performed on 2D slices through a 3D mass.

2.1. Potential Failure Mass, Slip Direction, and Weight

To assess stability throughout a DEM, Scoops3D typically computes factor of safety values, *F*, for thousands to millions of potential failure masses. Methods for searching the DEM and determining the lowest stability for each DEM cell are described in the next chapter (section 3.2). Here, we present the process for defining one potential failure mass in the DEM and then computing the stability of this mass.

Our analysis begins by defining a ***potential failure mass*** bounded by a trial surface that is part of a sphere. The center of this sphere can be any arbitrary point above the DEM. We then determine the DEM columns contained within the potential failure mass above the trial surface and beneath the DEM (fig. 2.1). This mass is composed of an ensemble of 3D vertical columns; the locations and horizontal dimensions of full columns within the mass are defined by the DEM grid orientation and cell size, allowing easy integration with the DEM. Some of the columns along the edge of the potential failure mass may be only partly contained within the bounds of the sphere. Scoops3D includes partial columns in the stability computation of the mass if two or three corners of the column at the ground surface are contained within the spherical trial surface. Column corner elevations are computed as the average of the four surrounding DEM cell elevations. For a given DEM resolution, the inclusion of partial columns leads to more accurate approximations of volume, weight, and the slip surface area for a potential failure mass, as compared to using only full columns, especially if a potential failure mass includes only a small number of full columns.

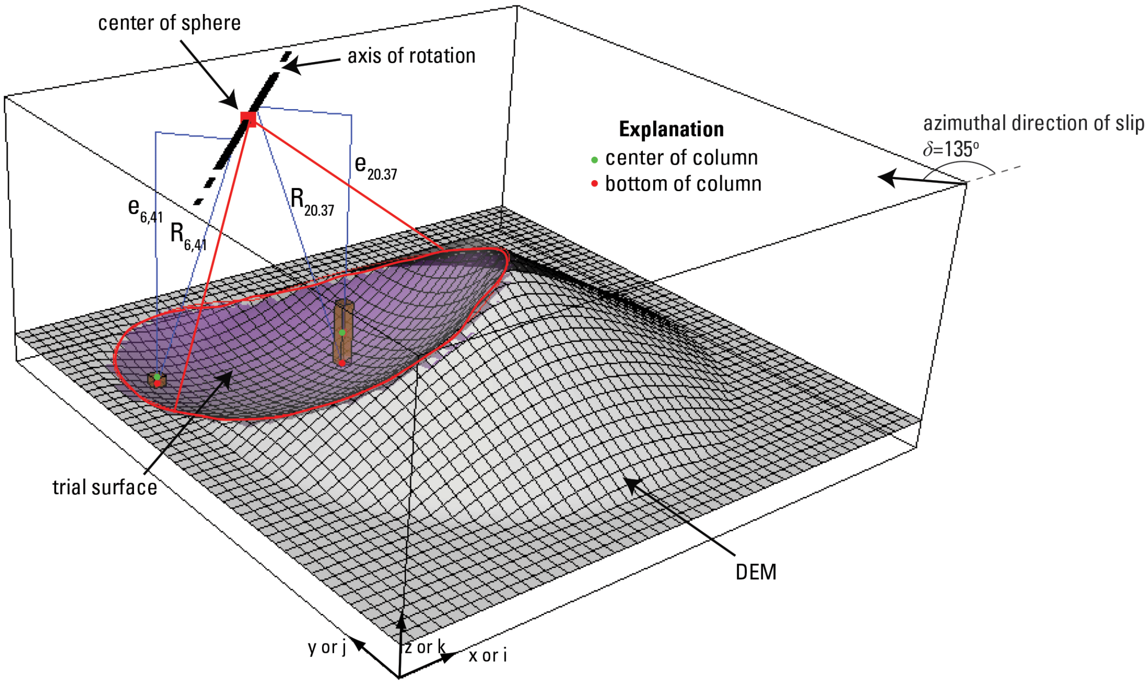


Figure 2.1. Diagram showing a 3D perspective view of a cone-shaped digital elevation model (DEM) and one potential failure (trial) surface. The potential failure mass (removed from this diagram) is composed of an ensemble of columns defined by the DEM grid with the center of the spherical trial surface and the axis of rotation located above the DEM. Two columns (in brown) of the potential failure mass are shown; each column has a different distance from the column base to the axis of rotation ($R_{i,j}$), where i,j denotes the DEM cell location. Horizontal earthquake loading, if selected by the user, is applied to the center of the columns and uses the vertical distance from the rotational axis ($e_{i,j}$), in the limit-equilibrium calculations (see section 2.3). The azimuthal direction of slip (perpendicular to the axis of rotation), δ, is shown in the upper right corner.

At the base of each column, the spherical trial surface is approximated locally as a plane dipping at angle ε. Given a spherical radius *R*, the slope of the trial surface through the center of each column is computed by taking the partial derivatives ($\partial z/\partial x$ and $\partial z/\partial y$) of the equation for the spherical surface:

$$R^2 = x^2 + y^2 + z^2, \tag{2.1}$$

where *x*, *y*, and *z* are orthogonal coordinates relative to the sphere center and defined in space by the DEM. The true dip of the trial surface, ε, and the apparent dip in the direction of slide movement, α, are computed using the equations:

$$\varepsilon = \cos^{-1}\left[1/\sqrt{1+(\partial z/\partial x)^2+(\partial z/\partial y)^2}\right], \text{ and} \tag{2.2}$$

$$\alpha = \tan^{-1}[(\partial z/\partial x)\cos\delta + (\partial z/\partial y)\sin\delta], \tag{2.3}$$

where δ is the azimuthal angle of the slide movement direction, measured counterclockwise from zero in the positive x direction (fig. 2.2*A*). Positive values of ε dip in the direction of potential sliding.

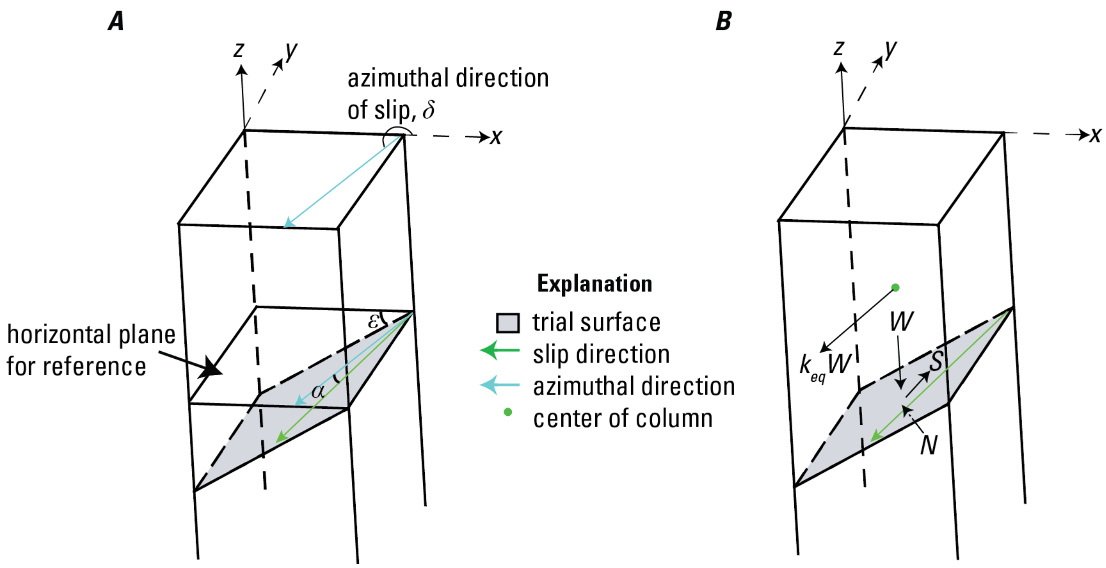


Figure 2.2. Schematic diagrams showing slip direction and forces acting on a 3D column. *A*, Diagram showing slip direction (green), true dip of the trial surface, ε, apparent dip in the direction of slip, α, and the azimuthal direction of slip, δ (blue). In this case the slip direction differs from the true dip direction of the trial surface, ε; this difference is common with 3D trial surfaces. Note that the trial surface is approximated as a plane at the base of each column. *B*, Diagram showing forces acting on the 3D column. The weight of the column (*W*), the normal force perpendicular to the trial slip surface (*N*), and the resisting shear force acting against slip (*S*) all act on the trial slip surface. The horizontal earthquake loading, $k_{eq}W$, acts at the center of the column in the azimuthal direction of slip, δ.

As part of the slope-stability analysis, Scoops3D computes the weight, W_c, of each column in the potential failure mass. The weight is computed by first determining the volume, V_c, of each column (partial or full) above the trial surface using an approximation for prismoids:

$$V_c = (1/6)\Delta x(S_0 + 4S_1 + S_2)\,, \tag{2.4}$$

where Δx represents the DEM grid spacing, S_0 and S_2 are the surface areas of the two parallel sides of the column, and S_1 is the surface area of a vertical cross section through the middle of the column (fig. 2.3). Scoops3D approximates S_1 using the average lengths of the two parallel sides of the column. Surface areas of the sides are computed using the ground surface elevations and the slip surface elevations at the corners of the column. Slip surface elevations are calculated using the equation of the sphere and the x and y locations of each column corner.

For full columns, where Δy_1 equals Δy_2 (fig. 2.3*B*), the equations for side areas are exact for quadrilaterals, where:

$$S_0 = (1/2)(\Delta z_1 + \Delta z_4)\Delta y_1\,, \tag{2.5a}$$

$$S_1 = [(1/4)(\Delta z_1 + \Delta z_2 + \Delta z_3 + \Delta z_4)][(1/2)(\Delta y_1 + \Delta y_2)]\text{, and} \tag{2.5b}$$

$$S_2 = (1/2)(\Delta z_2 + \Delta z_3)\Delta y_2\,. \tag{2.5c}$$

In this case, the volume is that of a prismoid although both the trial surface area and volume are slightly underestimated because the trial surface at the column base is approximated by a planar surface rather than the curve of a sphere. For partial columns that include two nodes, as illustrated in figure 2.3*A*, Δz_3 and Δz_4 equal zero, so the equation for area reduces to that for a triangle and the volume is that of a pyramid. For partial columns that include three nodes, the shape of one side is approximately a quadrilateral, whereas the other side is a triangle. This represents a more complex solid. In the three-node case, equation 2.4 does not account for the extra volume of the pyramid contained outside of the solid defined between the quadrilateral and triangular surfaces; Scoops3D calculates this volume separately and adds it to the total. Partial columns with only one corner node within the potential failure mass are ignored. By including partial columns in the trial failure mass, Scoops3D can typically provide accurate estimates of factor of safety and potential failure volume with only ~200–500 columns in the mass (see section 6.6), rather than the thousands of columns that may be needed in other approaches that use only full columns (for example, Lam and Fredlund [1993] and Huang and others [2002]). Columns in the potential failure mass (full or partial columns with two or three corner nodes) that are used for computations in Scoops3D are designated ***active columns***.

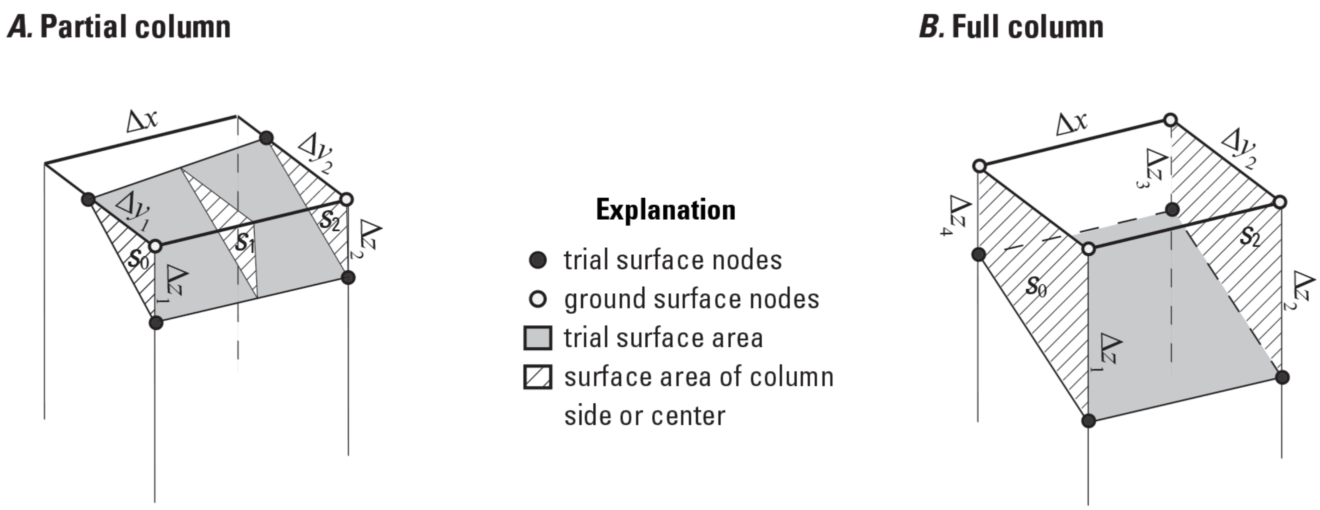


Figure 2.3. Schematic diagram of 3D partial and full columns showing components used to compute column volume above a trial slip surface. Scoops3D assumes a planar trial surface at the base of each partial or full column. *A*, Partial column showing two corner nodes within the potential failure mass. *B*, Full column encompassing a DEM cell.

Then column weight is computed using the column volume,

$$W_c = \int V_c \gamma(z)\, dz\,, \tag{2.6}$$

where γ is the unit or specific weight of the material, which may vary with depth, z. If the column contains more than one material with different properties, volumes and weights are appropriately integrated piecewise in the column above the trial surface. Scoops3D allows different unit weights for each material depending on the groundwater configuration selected. When a no groundwater or r_u option is selected, Scoops3D applies the user-defined total unit weight to each material. For stability analyses that include either a piezometric surface or positive pore-pressure heads defined in a 3D file, Scoops3D uses partially saturated unit weights above the uppermost water table (piezometric surface or zero pressure surface) and saturated weights below. With a 3D variably saturated pressure-head file, Scoops3D integrates the column weight by computing partially saturated unit weights using the vertical distribution of moisture content.

A trial surface constructed as part of a sphere could slip in any direction, and the different potential slip directions may result in different computed factors of safety. Although the trial surface shape is relatively symmetrical (depending on the roughness of the topography intersected by the sphere), the distribution of stresses acting on the trial surface may be asymmetrical due to variations in weight and pore pressure acting on different columns. Scoops3D always computes a factor of safety for a slip direction, δ, in the ***overall fall direction***, defined as the average ground-surface direction for all full DEM cells encompassed by the potential failure mass.

This fall direction is calculated using the arctangent of the sum of the slopes for the DEM cells in the x- and y-directions, $\sum \frac{dz}{dx}$ and $\sum \frac{dz}{dy}$ (see section 4.5.1.5 for definitions), converted to degrees from radians, and translated to a range of 0 to 360° where 0° coincides with the positive x-axis. Note that this is an azimuthal direction for the overall ground-surface slope of the potential failure mass, not the ground-surface slope itself. The user can opt to compute stability for additional slip directions on either side of the overall fall direction using the same trial surface to search for a minimum factor of safety (see section 4.4.1.1.9). The slip direction that yields the lowest factor of safety is a function of the distribution of stresses.

The axis of rotation (see fig. 2.1) changes orientation to remain perpendicular to any given slip direction and does not need to be aligned with the x-y orthogonal coordinates of the DEM. This feature is unlike typical 3D analyses that constrain slip to one direction parallel to the column grid. Because the stability calculations (section 2.3) do not require computation of lateral forces between the columns and because precision is enhanced by incorporating the effects of partial columns, Scoops3D can adequately compute stability for slip in any direction anywhere in the DEM, not just for slip aligned with x-y orthogonal coordinates. This capability is verified by the symmetry test described in section 6.7.

2.2. Shear Strength

In performing a slope-stability analysis, Scoops3D calculates the shear strength, *s*, on the trial surface by applying a linear Coulomb-Terzaghi failure rule:

$$s = c + (\sigma_n - u)\tan\phi \, , \tag{2.7}$$

where c is cohesion, ϕ is the angle of internal friction, σ_n is the normal stress, and u is the pore-water pressure acting on the shear surface. This rule can accommodate many standard geotechnical analyses, including total stress (where $u = 0$) and effective stress ($u \neq 0$), as well as undrained ($\phi = 0$) analyses. This equation allows the user to set c, ϕ, and u to any values appropriate for the desired analyses. For example, a geotechnical effective stress analysis would use c' and ϕ', where the prime symbol denotes values for effective stress. Depending on the analysis, ϕ might represent peak, residual, or critical-state frictional strength (Manzari and Nour, 2000). In the following mathematical presentation we use c and ϕ for simplicity, although they may represent total or effective stress values as selected by the user.

Pore pressures in unsaturated materials (or matric suctions having negative values relative to the air pressure in the pores) induce suction stresses that can increase frictional strength when mobilized in shear.

Previous investigators (Vanapalli and others, 1996; Vanapalli and Fredlund, 2000; Lu and Griffiths, 2004) have found that the effects of suction stress can be reasonably approximated solely as a function of the effective degree of saturation:

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)}, \tag{2.8}$$

where θ is the water content, θ_r is the residual water content, and θ_s is the saturated water content. The parameter S_e, which has values <1 in partially saturated materials, directly scales the effects of suction, thereby reducing the effects of matric suction (negative pressures) relative to those of equivalent positive pore pressures. The Coulomb-Terzaghi failure rule can be combined with S_e to obtain a failure rule for partially saturated materials (where here, u can be negative and reflects matric suction):

$$s = c + (\sigma_n - S_e u)\tan\phi . \tag{2.9}$$

Note that in this approach, the same values of c and ϕ are assumed for both saturated and partially saturated materials (Vanapalli and Fredlund, 2000; Lu and Likos, 2004; Lu and Godt, 2013); this differs from some other approaches (Bishop and Blight, 1963; Fredlund and others, 1978). If the user wants to include pore-pressure effects in unsaturated as well as saturated materials, Scoops3D has an option to include 3D variably saturated pore-pressure heads and the associated water contents needed to compute values of S_e (section 2.4). With this option, Scoops3D assumes $S_e = 1$ for saturated materials and thereby computes strength using the standard Coulomb-Terzaghi rule. A similar approach has been used in analyses of one-dimensional slope stability (Lu and Godt, 2008; Godt and others, 2009; Baum and others, 2010).

At the base of each 3D column in a potential failure mass, Scoops3D uses the c and ϕ values of the material intersected by the trial surface in the center of the column for computation of slope stability. Assignment of c and ϕ values is governed by vertical elevation. If the user has defined material layers, then Scoops3D uses the values of c and ϕ for the layer at the elevation of the base of each column. If the user has provided a full 3D distribution of strengths (section 4.4.2.2), then the precise selection of values depends on the user-defined structure of the data. Scoops3D will either interpolate between adjacent vertical point values (if the linear interpolation option is selected) or use the value of the block containing the trial surface elevation (if the data is treated as discrete finite blocks with fixed parameters– see section 4.4.2.2).

2.3. General Moment Equilibrium

Scoops3D computes a factor of safety, F, for a given trial surface using moment equilibrium. This section presents the general approach and the two subsequent sections detail the differences between the Ordinary (Fellenius) and Bishop's simplified methods. In general, all limit-equilibrium methods (including moment equilibrium methods) define F as the ratio of the average shear resistance (strength), s, to the shear stress, τ, required to maintain limiting equilibrium along a predefined trial surface:

$$F = \frac{s}{\tau}. \tag{2.10}$$

Values of F less than one indicate instability. A constant proportion $1/F$ of the available shear strength resists the shear stress at equilibrium (a fundamental assumption of the method), or:

$$\tau = \frac{s}{F}. \tag{2.11}$$

For finite areas, such as the total trial surface or the base of an individual column, we need to use quantities of force, or stress acting over an area. Thus the average resisting shear force at equilibrium, T, is:

$$T = (1/A)\int_A [(sA)/F]dA, \tag{2.12}$$

where A is the total trial surface area. Discretizing the shear resistance over an ensemble of vertical columns in the potential failure mass, defined by a DEM and indexed by i and j in the x and y directions respectively, leads to:

$$T = \frac{1}{F}\sum s_{i,j}A_{i,j}, \tag{2.13}$$

where $A_{i\,j}$ is the area of the trial surface at the base of each i, j column. The value of $A_{i\,j}$ varies depending on the slope of the base and whether the column encompasses a full or partial DEM cell. F is assumed to be the same for each column.

For a potential failure mass bounded by a spherical trial surface, Scoops3D calculates the equilibrium of moments about a rotational axis through the center of the sphere. The axis is horizontal and oriented normal to the slip direction of the potential failure mass (see fig. 2.1). Note that a given trial surface may rotate around an axis oriented in any direction within the horizontal plane.

In Scoops3D, the driving moment is derived from two types of forces: gravitational weight (W) acting in the vertical direction and, if the user selects earthquake or seismic loading, a uniform horizontal force ($k_{eq}W$). This force results from a horizontal pseudo-acceleration coefficient, k_{eq}, a dimensionless coefficient typically expressed as a fraction of g (the magnitude of gravitational acceleration), acting on the weight. This simple method of incorporating earthquake loading is commonly termed a pseudo-static analysis. Scoops3D applies a uniform value of k_{eq} in the horizontal direction aligned with slip. With no earthquake loading, the k_{eq} coefficient equals zero.

The moment arm associated with the gravitational force on each column is equal to the horizontal distance from the axis of rotation to the center of mass of the column (approximated as the geometric center of the column). Positive distances are directed upslope of the axis of rotation. By geometry:

$$a_{i,j} = R_{i,j} \sin \alpha_{i,j} , \tag{2.14}$$

where $R_{i,j}$ is the distance from the axis of rotation to the center of the base of a column and $\alpha_{i,j}$ is the apparent dip of the column base in the direction of rotation. Note that in 3D, $R_{i,j}$ will vary from column to column because it is the distance to the rotational axis (see fig. 2.1); in a 2D method of slices, R is constant and equal to the radius of a circle. Therefore, the driving moment due to the weight of the columns, M_d, is:

$$M_{d,gravity} = \sum R_{i,j} W_{i,j} \sin \alpha_{i,j} . \tag{2.15}$$

The driving moment due to a uniform horizontal force from earthquake loading is:

$$M_{d,earthquake} = \sum W_{i,j} k_{eq} e_{i,j} , \tag{2.16}$$

where $e_{i,j}$ is the horizontal driving force moment arm for a column (equal to the vertical distance from the center of the column to the elevation of the axis of rotation, see fig. 2.1). This horizontal force acts in the azimuthal direction of slip. Note that the normal forces on the base of each column act through the axis of rotation and thus produce no moment.

The resisting moment is the sum of the products of the shear stresses on the base of each column (equation 2.17) and the resisting moment arms, equal to the distance from the column base to the axis of rotation. The total resisting moment for the ensemble of columns becomes:

$$M_r = \sum R_{i,j} \frac{s_{i,j} A_{i,j}}{F} . \tag{2.17}$$

Substituting $S_{i,j}$ from equation 2.7 into the resisting moment:

$$M_r = \sum R_{i,j} \frac{c_{i,j} A_{i,j} + (\sigma_{n_{i,j}} - u_{i,j}) A_{i,j} \tan \phi_{i,j}}{F} \text{, or} \tag{2.18}$$

$$M_r = \sum R_{i,j} \frac{c_{i,j} A_{i,j} + (N_{i,j} - u_{i,j} A_{i,j}) \tan \phi_{i,j}}{F} , \tag{2.19}$$

where $N_{i,j}$ is the normal force, $\sigma_{n_{i,j}} A_{i,j}$, acting on the column base. Here, values of $c_{i,j}$ and $\tan \phi_{i,j}$ are for the trial surface at the *i,j* column.

The global moment equilibrium, M, for rotation about the axis through the center of the trial surface sphere equals zero, and is defined by:

$$M = 0 = M_r - M_{d,gravity} - M_{d,earthquake}, \tag{2.20}$$

or for all columns:

$$\sum M = \sum R_{i,j} \frac{c_{i,j}A_{i,j} + (N_{i,j} - u_{i,j}A_{i,j})\tan\phi_{i,j}}{F} - \sum W_{i,j}R_{i,j}\sin\alpha_{i,j} - \sum W_{i,j}k_{eq}e_{i,j}\ . \tag{2.21}$$

A factor of safety, F, against rotation can then be defined as:

$$F = \frac{\sum R_{i,j}(c_{i,j}A_{i,j} + (N_{i,j} - u_{i,j}A_{i,j})\tan\phi_{i,j})}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}\ . \tag{2.22}$$

If $\phi \neq 0$, then the normal force, $N_{i,j}$, acting on the slip surface of each column must be determined. The Ordinary (Fellenius) and Bishop's simplified methods use different procedures to estimate these normal forces, as discussed in sections 2.3.1 and 2.3.2.

2.3.1. Ordinary (Fellenius) Method

The Ordinary method was first developed by Fellenius (1936) to compute stability on a 2D slip circle divided into slices. In Scoops3D, we extend this method to 3D columns and add the capability to include earthquake loading effects in a pseudo-static analysis. In contrast to the 2D approach, 3D slip can occur in directions other than the true dip of the trial surface (section 2.1). Shear force, $S_{i,j}$, (positive in the upward direction) resists movement in the slip direction and thus is a function of the apparent dip of the trial surface. To compute the normal force, $N_{i,j}$, acting on the slip surface for a given column (see fig. 2.2*B*), we resolve the vertical (equation 2.23) and horizontal (equation 2.24) force equilibrium equations driven by the weight, $W_{i,j}$, acting vertically, and earthquake loading, $k_{eq}W_{i,j}$, acting horizontally in the direction of slip:

$$W_{i,j} = N_{i,j}\cos\varepsilon_{i,j} + S_{i,j}\sin\alpha_{i,j}\text{, and} \tag{2.23}$$

$$k_{eq}W_{i,j} = S_{i,j}\cos\alpha_{i,j} - N_{i,j}\frac{\cos\varepsilon_{i,j}}{\cos\alpha_{i,j}}\sin\alpha_{i,j}\ . \tag{2.24}$$

Note that the horizontal force equilibrium (equation 2.24) includes the component of the normal force acting in the slip direction. Solving this equation for $S_{i,j}$ gives:

$$S_{i,j} = \frac{1}{\cos\alpha_{i,j}}\left[N_{i,j}\frac{\cos\varepsilon_{i,j}}{\cos\alpha_{i,j}}\sin\alpha_{i,j} + k_{eq}W_{i,j}\right], \tag{2.25}$$

and substituting $S_{i,j}$ back into the vertical force equilibrium (equation 2.23) produces:

$$W_{i,j} = N_{i,j}\cos\varepsilon_{i,j} + \frac{\sin\alpha_{i,j}}{\cos\alpha_{i,j}}\left[N_{i,j}\frac{\cos\varepsilon_{i,j}}{\cos\alpha_{i,j}}\sin\alpha_{i,j} + k_{eq}W_{i,j}\right]. \tag{2.26}$$

Solving for N_{ij}, multiplying each side by $\cos^2\alpha_{i,j}$, and simplifying yields:

$$N_{i,j} = W_{i,j}\frac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[1 - k_{eq}\tan\alpha_{i,j}\right]. \tag{2.27}$$

This definition of normal force is based on the assumption that forces on the sides of the column in the slip direction act parallel to the base of the column. This assumption is physically implausible (given that each column has a base with a different slope), except when the intercolumn forces are zero. Therefore, the Ordinary method, and Scoops3D implementation of it, explicitly neglects all side forces on the columns and assumes they are zero. Note that, even neglecting side forces, the Ordinary method utilizes moment equilibrium and thus differs from the method proposed by Hovland (1977). Hovland's method, applied to uniform slopes, often leads to lower computed factor-of-safety values than either the Ordinary method or more rigorous methods (Ugai, 1988; Xie and others, 2006b).

The Ordinary method in 2D may underestimate F when high pore pressures act on the trial slip surface (Whitman and Bailey, 1967; Duncan and Wright, 1980, 2005). To compensate, some investigators have proposed using an effective column weight to account for pore-water pressure effects (Turnbull and Hvorslev, 1967). Other researchers have examined the ramifications of these different approaches (Lei and others, 2011). On the basis of those studies and our own experience, we have chosen to implement the Ordinary method with one modification - when the resisting force at the base of any column is negative, we assume the force for this column is zero in the overall moment equilibrium (see special cases, in section 2.5). Results obtained using this approach are typically closer to those derived from Bishop's simplified method than results from either the traditional Ordinary method or results obtained using modifications based on effective column weight (Turnbull and Hvorslev, 1967; Duncan and Wright, 2005), even for cases with high pore pressures (Lei and others, 2011).

Substituting the 3D Ordinary definition of normal force (equation 2.27) into the general moment equilibrium factor-of-safety equation 2.22 gives:

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right] - u_{i,j}A_{i,j}\right)\tan\phi_{i,j}\right]}{\sum W_{i,j}\left[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}\right]}. \tag{2.28}$$

Because rotation in 3D is around an axis, values of $R_{i,j}$ vary between columns and they are retained in the final equation for F. In the 2D version of the Ordinary method, R is constant and cancels out of the final equation.

2.3.2. Bishop's Simplified Method

Bishop's simplified method was also developed as a 2D method of slices (Bishop, 1955). Bishop's simplified method determines the normal force acting on the slip surface by first computing force equilibrium in the vertical direction on the base of each slice. The side forces on the slices are assumed to be horizontal (with no net shear stress between slices) and are not explicitly used in the method. Our 3D implementation of this method (Reid and others, 2000) makes the same assumptions for columns and follows a procedure similar to that presented by Hungr (1987) and Hungr and others (1989).

Vertical force equilibrium on the base of a column is found using equation 2.23. In the 3D extension of this method (Hungr, 1987; Hungr and others, 1989), the vertical normal force component is resolved with respect to the true dip of the trial surface at the column base, $\varepsilon_{i,j}$. The shear force on the base acts parallel to the apparent dip in the direction of potential sliding, so the vertical component is resolved with respect to $\alpha_{i,j}$, as in our 3D extension of the Ordinary (Fellenius) method (section 2.3.1). Shear force, $S_{i,j}$, on the base of the column is a function of shear strength and the factor of safety, F:

$$S_{i,j} = \frac{1}{F}[c_{i,j}A_{i,j} + (N_{i,j} - u_{i,j}A_{i,j})\tan\phi_{i,j}]. \tag{2.29}$$

Combining equations 2.23 and 2.29 and rearranging gives:

$$N_{i,j}\cos\varepsilon_{i,j} + \frac{N_{i,j}\tan\phi_{i,j}\sin\alpha_{i,j}}{F} = W_{i,j} - \frac{c_{i,j}A_{i,j}\sin\alpha_{i,j}}{F} + \frac{u_{i,j}A_{i,j}\tan\phi_{i,j}\sin\alpha_{i,j}}{F}, \tag{2.30}$$

and solving for $N_{i,j}$:

$$N_{i,j} = \frac{W_{i,j} - \frac{c_{i,j}A_{i,j}\sin\alpha_{i,j}}{F} + \frac{u_{i,j}A_{i,j}\tan\phi_{i,j}\sin\alpha_{i,j}}{F}}{[\cos\varepsilon_{i,j} + (\sin\alpha_{i,j}\tan\phi_{i,j})/F]}. \tag{2.31}$$

For convenience, the denominator of this equation, , is common $\cos\varepsilon_{i,j} + (\sin\alpha_{i,j}\tan\phi_{i,j})/F$ is commonly termed $m_{\alpha_{i,j}}$. Substituting the normal force, $N_{i,j}$, into the moment equilibrium factor-of-safety equation 2.22 gives:

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{\left[W_{i,j} - \frac{c_{i,j}A_{i,j}\sin\alpha_{i,j}}{F} + \frac{u_{i,j}A_{i,j}\tan\phi_{i,j}\sin\alpha_{i,j}}{F}\right]}{m_{\alpha_{i,j}}} - u_{i,j}A_{i,j}\right)\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}. \tag{2.32}$$

With considerable simplification, and noting that the horizontal area of the column base, $A_{h_{i,j}} = A_{i,j} \cos\varepsilon_{i,j}$, the equation for F becomes:

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + (W_{i,j} - u_{i,j}A_{h_{i,j}})\tan\phi_{i,j}] / m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]} . \quad (2.33)$$

Because the numerator, or resisting moment, is a function of the factor of safety, F, the solution to equation 2.33 is obtained using an iterative method. The method requires an initial estimate of factor of safety, F_i, and convergence of the iterative process can be sensitive to F_i; for example, it is possible to converge to an inaccurate F value if the trial surface has a steep dip oriented against rotation (negative ε). If any column on the trial surface has a negative value of dip, ε, then Scoops3D uses an initial estimate of factor of safety, F_i:

$$F_i = F_O + \beta_{3D} , \quad (2.34)$$

where F_O is the factor of safety found using the Ordinary Method for the same potential failure mass and:

$$\beta_{3D} = \frac{(-\sin\alpha_m \tan\phi_m)}{\cos\varepsilon_m} , \quad (2.35)$$

where m denotes the column with the maximum negative ε value. This approach is similar to that proposed by Chowdhury and Zhang (1990) for 2D analyses, except that we use F_O instead of 1 and a 3D version of their ß. It is important in these cases that $F_i > ß_{3D}$, otherwise some m_α values can be negative and the iterations will not converge to the correct result. If no columns on the trial surface have a negative ε, then Scoops3D uses $F_i = F_O$. Using these approaches, most solutions converge in 4–5 iterations. Note that even with the selection of F_i as described above, the iterations may not converge for a particular trial surface. This is usually due to the inability to obtain a reasonable normal force on the base of a column, typically where the slip surface is very steep and (or) affected by high pore pressures. If the solution for F does not converge monotonically in 10 iterations, Scoops3D will terminate computations for that trial surface. If solutions converge monotonically, then Scoops3D will continue up to a maximum of 25 iterations before terminating and advancing to the next trial surface. Trial slip surfaces that do not converge in the allowed number of iterations are assigned an arbitrarily large factor of safety value of 111.0 for identification purposes. Scoops3D records all non-converging trial surfaces in an output file for inspection by the user (section 4.5.2.3), but does not halt overall program execution.

2.4. Pore-Water Pressure Conditions

Determining the pore-water pressure acting on each column base can be difficult owing to complex gravity-driven groundwater flow that creates spatially variable conditions. Therefore, stability analyses commonly make simplifying assumptions to characterize the pore-pressure field. Scoops3D allows the user to select from several different methods to account for pore-water pressure effects in the stability analysis; these include (1) no groundwater pressure, (2) a pore-pressure ratio, r_u, (3) a piezometric surface, (4) a 3D distribution of saturated pore-pressure heads, or (5) a 3D distribution of variably saturated pore-pressure heads. Each of these options makes different assumptions about the distribution of pore pressure, which results in slight variations in the factor of safety equation used in Scoops3D. Note that pore pressure, *u*, is related to pressure head, *h* (in units of length), by:

$$u = h\gamma_w . \tag{2.36}$$

The equations for each method are summarized in table 2.1.

Table 2.1. Equations for factor of safety, *F*, given different pore-pressure conditions.

(1) No groundwater

Ordinary (Fellenius)

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \dfrac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right]\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

Bishop's simplified

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + W_{i,j}\tan\phi_{i,j}]/m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

(2) Pore-pressure ratio

Ordinary (Fellenius)

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \dfrac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right](1 - r_{u_{i,j}})\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

Bishop's simplified

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + W_{i,j}(1 - r_{u_{i,j}})\tan\phi_{i,j}]/m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

(3) Piezometric surface

Ordinary (Fellenius)

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right] - z_{pz_{i,j}}\gamma_w A_{i,j}\right)\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

Bishop's simplified

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + (W_{i,j} - z_{pz_{i,j}}\gamma_w A_{h_{i,j}})\tan\phi_{i,j}]/m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

(4) 3D pressure heads

Ordinary (Fellenius)

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right] - u_{i,j}A_{i,j}\right)\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

Bishop's simplified

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + (W_{i,j} - u_{i,j}A_{h_{i,j}})\tan\phi_{i,j}]/m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

(5) 3D variably saturated pressure heads

Ordinary (Fellenius)

$$F = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{\cos^2\alpha_{i,j}}{\cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}\tan\alpha_{i,j}\right] - S_{e_{i,j}}u_{i,j}A_{i,j}\right)\tan\phi_{i,j}\right]}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

Bishop's simplified

$$F = \frac{\sum R_{i,j}[c_{i,j}A_{h_{i,j}} + (W_{i,j} - S_{e_{i,j}}u_{i,j}A_{h_{i,j}})\tan\phi_{i,j}]/m_{\alpha_{i,j}}}{\sum W_{i,j}[R_{i,j}\sin\alpha_{i,j} + k_{eq}e_{i,j}]}$$

If the pore-pressure ratio option is selected, then the user enters a r_u value for each material layer. The pore-pressure ratio, r_u, as defined by (Bishop, 1955) is equivalent to:

$$r_u = \frac{u}{\int \gamma_t z dz} = \frac{u}{(W/A_h)}, \tag{2.37}$$

where γ_t is the total unit weight of the overlying material. This ratio represents the pore pressure divided by the integrated total vertical gravitational stress at the same location, and is typically used to account for relatively uniform pore-pressure effects along the trial surface. Note that using one average r_u value can over- or underestimate actual pore-water pressures (Eid, 2010).

If the user selects the piezometric surface option, Scoops3D uses a grid containing the elevations of the piezometric surface to determine pore pressures acting on the trial surface at the base of each column. This option assumes that pore pressures are hydrostatic with vertical depth, where

$$u = z_{pz}\gamma_w \tag{2.38}$$

and z_{pz} is the vertical depth below the piezometric surface and can vary between columns. This option can be used to represent horizontal saturated groundwater flow beneath a water table.

A 3D distribution of pressure heads (for example, from a groundwater flow model) can be used to compute pore pressure (using equation 2.37) in Scoops3D. To use this option, the user provides a separate input file containing 3D pressure-head values for each DEM cell using the 3D file formats presented in section 4.4.2.2. Scoops3D computes the pore pressure acting on the base of each column by linearly interpolating between vertical values of pressure head on either side of the trial surface. All values of $u < 0$ on a column base are set to zero when using this option.

Scoops3D also allows the user to incorporate the pore-pressure effects of a 3D variably saturated groundwater flow field, where flow may occur in either or both partially saturated ($u < 0$) and saturated materials. Pore-water pressures in partially saturated materials are negative relative to atmospheric pressure (reflecting matric suction), and the relation between water content and pressure is often highly nonlinear (Hillel, 1980). The negative pressures impart an inter-particle stress that acts to increase shear resistance (see section 2.2). As with the 3D pressure-head option described above, Scoops3D performs a linear interpolation between vertical values on either side of the slip base to determine the pore pressure (positive or negative) acting on the base of each column. In partially saturated materials, values of water content are needed to compute the effective degree of saturation, S_e that influences shear strength (section 2.2). Scoops3D has three options to obtain these values: (1) provide a 3D file containing locations with corresponding variably saturated pressure head and water content, (2) use parameters for a van Genuchten (1980) soil-water characteristic curve (SWCC) as well as a 3D file containing variably saturated pressure heads, or (3) use parameters for a Fredlund and Xing (1994) SWCC as well as a 3D file containing variably saturated pressure heads. Use of a SWCC enables direct computation of water content given a soil matric suction, ψ (suction is opposite in sign to pore pressure). Note that a SWCC function can be obtained by curve fitting measured data or by assuming appropriate parameters.

The van Genuchten SWCC formula, using the Mualem (1976) model assumption, is:

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha_{vG}\psi)^{n_{vG}}]^{(1-1/n_{vG})}}, \tag{2.39}$$

where α_{vG} and n_{vG}, are curve parameters. With the van Genuchten SWCC or with the 3D water content file options in Scoops3D, if any water content is less than θ_r, then suction stress effects for this location equal zero in the stability calculations.

The Fredlund and Xing (1994) SWCC formula, as presented in Fredlund and others (2012), is:

$$\theta(\psi) = C(\psi)\frac{\theta_s}{\{\ln[e + (\psi / a_{FX})^{n_{FX}}]\}^{m_{FX}}}, \tag{2.40}$$

where $C(\psi)$, a correction factor, is:

$$C(\psi) = 1 - \frac{\ln(1 + \psi / \psi_r)}{\ln[1 + (1000000 / \psi_r)]}, \tag{2.41}$$

α_{FX}, n_{FX}, and m_{FX} are curve parameters, and ψ_r is the soil matric suction at residual conditions. With the Fredlund and Xing SWCC option in Scoops3D, if any pore pressure is lower (drier) than ψ_r, then pore pressure and suction stress are set to zero.

2.5. Special Cases

During the computation of factor of safety, certain conditions can arise that are physically implausible for a given trial surface. Scoops3D attempts to identify and correct for these special cases without halting execution of the program. For example, if a negative frictional resisting force is determined at the base of any column, that is:

$$\left(\frac{\cos^2\alpha_c}{\cos\varepsilon_c}W_c - uA_c\right)\tan\phi < 0 \text{ (Ordinary), or} \tag{2.42}$$

$$(W_c - uA_h)\tan\phi < 0 \text{ (Bishop's simplified),} \tag{2.43}$$

then Scoops3D assigns a value of zero frictional resisting force for that column and continues to determine *F* for the trial mass. This special case can occur when pore pressures are very high. When using the Ordinary method, if the sum of the resisting forces is less than zero, then Scoops3D sets the sum to zero. Therefore, shear resistance cannot create $F < 0$. In both methods, if the sum of the driving forces is less than zero, then Scoops3D sets *F* to 100 for identification purposes. Also, if the computed *F* in either method is very large (> 100), then Scoops3D sets $F = 100$ (compared to $F = 111.0$ for nonconverging solutions – see section 2.3.2).

2.6. Slope Stability of 2D Slice

For comparative purposes, Scoops3D computes a 2D factor of safety if the user elects to analyze a single surface in 3D. The 2D solution is obtained for a vertical section through the estimated center of the 3D mass with a trial slip surface oriented in the same direction as the 3D slip direction. The 2D center of rotation is defined by the intersection of a line projecting from the estimated center of the 3D mass in the plane defined by the slip direction and the 3D axis of rotation. A 2D method of slices, matching the stability method selected for the 3D analysis (Ordinary or Bishop's simplified), is used for the stability computation. Scoops3D determines the width of each slice (along the direction of slip) depending on the orientation of the cross section with respect to the columns; thus each slice will have a different width and cross-sectional area unless the slip direction coincides with either the x or y axis of the DEM. If the slip direction does coincide with one of axis directions, each slice will have a width equal to the DEM cell size. The arc length at the base of each 2D slice is found by dividing the intersecting slice width by the apparent dip in the slide direction of the 3D column base. Strength and groundwater conditions for each slice match those of the corresponding 3D column. The rotational moment arm (constant radius), dip and length of the slip base for each slice, and the earthquake moment arm (if using earthquake loading) are computed for the 2D analogs. A ratio of 2D cross sectional area to 3D volume is used to estimate the weight of each slice. Because of these approximations, the 2D factor of safety computed by Scoops3D may not precisely match the 2D factor of safety computed by other programs.

Chapter 3. Build and Search a 3D Domain

Scoops3D computes slope stability for all parts of a 3D domain underlying a digital elevation model (DEM). The user has a variety of options for building this 3D domain and configuring its material properties and groundwater conditions, ranging from very simple homogeneous earth materials to full 3D distributions of subsurface properties. Scoops3D determines the minimum stability associated with each DEM cell in the digital landscape. This objective makes Scoops3D different from most other 3D slope-stability models that typically search only for the single, least-stable potential failure for a given hillslope or embankment. In this chapter, we describe how to construct a 3D domain and how to perform a thorough search of the domain to identify the minimum stability for each DEM cell.

3.1. Construct a 3D Domain

In all cases, the user must provide a DEM that represents the ground surface of the 3D domain. The DEM defines the horizontal extent of the domain, and the DEM cell spacing defines the horizontal dimensions of the 3D columns used in the slope-stability computations. Scoops3D allows users to select from three approaches to define subsurface material properties and different groundwater configurations (table 3.1). In general, if the user wants to use layers and (or) 3D distributions of properties, then this information must be contained in separate files using the formats listed in section 4.4.2. The graphical user interface, Scoops3D-i (section 4.3), does not build these additional files; it does, however, check for their existence if the user has selected options using these files.

Table 3.1. Matrix of material properties and groundwater configuration options selectable in Scoops3D.

		Groundwater configuration				
		none	pore-pressure ratio, r_u	piezometric surface file	3D pressure-head file	3D variably saturated file
Material properties	Homogeneous	x	x	x	x	x
	Layer files	x	x	x	x	x
	3D file	x	x	x	x	

To examine the effects of topography alone on slope stability, the user can opt to use a simple homogeneous domain beneath the DEM. The user then assigns uniform values for the earth material in this domain; these values are contained in the main parameter input file (see section 4.4.1). In this scenario, stability will be a function of topography integrated over the size of potential failures analyzed.

If the location of spatially variable properties in the domain can be represented as a series of layers (each having its own properties), Scoops3D can readily accommodate the layered data using files that define the lowermost (bottom) elevation of each layer as a surface (in an ASCII raster grid format). This approach allows easy integration with Geographic Information System (GIS) or grid software, such as Esri ArcGIS, GRASS GIS, Quantum QGIS, or Golden Software Surfer; layers can be readily created and visualized with such software. Very simple layers (such as a flat boundary beneath the DEM) may be manually constructed with a text editor or spreadsheet program using an ASCII raster file of the DEM as a template.

For more complex scenarios with a variable 3D distribution of material properties and (or) pore-water pressures, Scoops3D reads separate input file(s) having the formats described in section 4.4.2.2. Typically these 3D data cannot be constructed in surface or layer-oriented GIS software, but instead are derived from 3D geophysical (for material properties) or groundwater flow (for pore-water pressure head) models. Manual construction of a complex 3D array is difficult. The user must exercise care in creating these files so that 3D data are provided for each DEM cell and the horizontal locations of nodes in any 3D data files align with the centers of the DEM cells.

The sections below describe options for defining different aspects of the 3D domain, including topography, material properties, pore-water pressures, and earthquake loading effects. Details of the file formats for the ASCII raster grid files and 3D data files are contained in section 4.4.2.

3.1.1. Topography

Ground-surface topography, denoting the upper boundary of the 3D domain, is represented by a digital elevation model (DEM). The DEM format required by Scoops3D contains an orthogonal array of equal sized cells, with each cell (raster) containing an elevation value (fig. 3.1). A DEM input file is mandatory for all Scoops3D analyses.

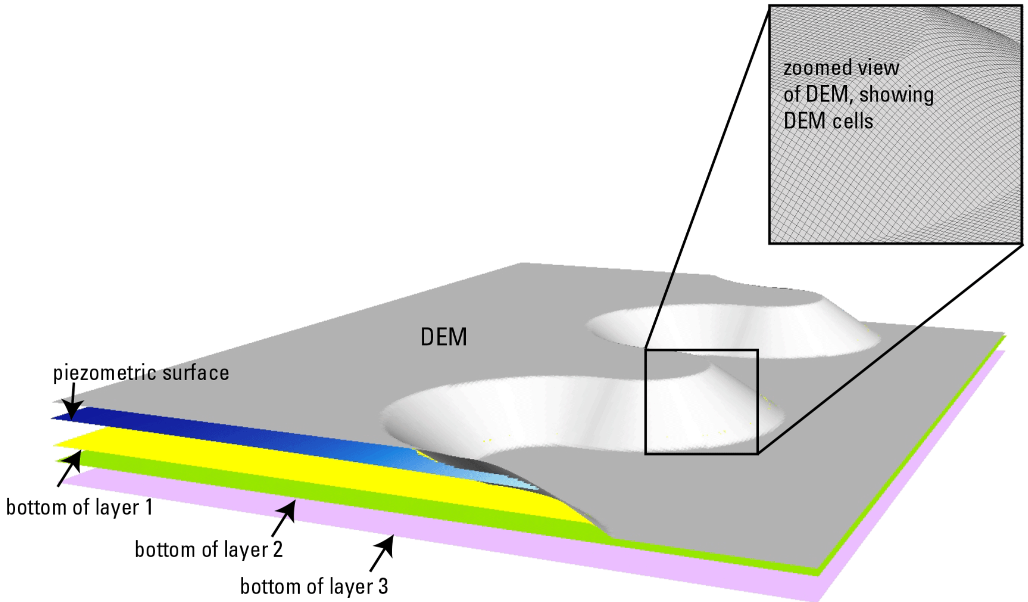


Figure 3.1. Perspective view of a digital elevation model (DEM) underlain by four material layers and a piezometric surface layer. Note that the fourth layer extends from the bottom of layer 3 to infinite depth. Inset shows detail of DEM cells.

DEM data can be obtained from a variety of sources, such as national elevation databases or lidar (Light Detection and Ranging) surveys. The DEM file used by Scoops3D must be structured in the Esri ASCII raster format, as described in section 4.4.2.1. If the user's DEM is in a different format, it must be converted. An example of converting a raster dataset using Esri's ArcGIS software is given in section 4.4.2.1.1. We have found that the boundaries of the DEM should extend slightly beyond the slopes of interest for the practical reasons discussed in section 5.3.3. Although Scoops3D can analyze a DEM of any grid cell size (resolution), the cell size has a considerable influence on both computational accuracy and efficiency. Higher resolution grids lead to more accurate calculations of factor of safety and volume, but they increase computational time and computer memory requirements. Choosing an appropriate DEM resolution is discussed in detail in section 5.3.4.

DEMs that include bodies of water (for example, lakes or oceans) as flat surfaces should be treated carefully. Potential failure masses intersecting flat water surfaces in a DEM will produce erroneous computations of factor of safety. Generally, the user should remove these flat surfaces from the DEM. Scoops3D does not compute the stability of partially submerged slopes. If bathymetry is available for fully submerged areas, Scoops3D can perform subaqueous stability computations in these areas if the user enters buoyant (instead of total) unit weights for the fully submerged materials. This approach assumes fully saturated, hydrostatic conditions in the submerged materials.

3.1.2. Material Properties in the Subsurface

Scoops3D requires the user to define properties (table 3.2) for all earth materials underlying the DEM. Some of these properties are needed to compute factors of safety for trial surfaces, whereas others are required only for specific groundwater configurations (table 3.2). The distribution of these properties can be defined using one of three approaches: (1) uniform, homogeneous properties, (2) layered material properties, or (3) 3D spatially varying properties (this third option is not available with variably saturated groundwater conditions). Layers and 3D distributions require additional input files. Only one of these three approaches can be used for a given model.

3.1.2.1. Homogeneous Properties

This option is the simplest; the spatial distribution is uniform with one material layer extending to infinite depth beneath the DEM. With this option, Scoops3D uses homogeneous properties in computing the factor of safety for a given trial surface. Values for both c and ϕ are required; these are contained in the main input file (section 4.4.1.1.4). Only total unit weight is required for no groundwater or pore-pressure ratio analyses, whereas both partially saturated and saturated unit weights are required for the piezometric surface and 3D pressure-head groundwater configurations. Residual and saturated water contents are required only with the 3D variably saturated option.

Table 3.2. List of properties required by Scoops3D for each earth material.

[Note that all parameters must be in internally consistent units, with length units that match the DEM. The properties required depend on the groundwater configuration selected, as indicated in the last seven columns of the table. SWCC is soil-water characteristic curve. ft, foot; kN, kilonewton; kPa, kilopascal; lb, pound; m, meter]

Property	Symbol	Parameter name	Examples of units	Required with specified groundwater configuration						
								3D variably saturated file		
				none	pore-pressure ratio, r_u	piezometric surface file	3D pressure-head file	water content in 3D file	vanGenuchten SWCC	Fredlund and Xing SWCC
Cohesion	c	***cee***	kPa or lb/ft^2	x	x	x	x	x	x	x
Angle of internal friction	θ	***phi***	degrees	x	x	x	x	x	x	x
Unit weight, total	γ_t	***gamt***	kN/m^3 or lb/ft^3	x	x					
Unit weight, partially saturated	γ_{ps}	***gamps***	kN/m^3 or lb/ft^3			x	x			
Unit weight, saturated	γ_s	***gams***	kN/m^3 or lb/ft^3			x	x	x	x	x
For variably saturated configurations:										
Residual water content	θ_r	***thetares***	Dimensionless					x	x	x
Saturated water content	θ_s	***thetasat***	Dimensionless					x	x	x
van Genuchten SWCC parameter	α_{vG}	***vgalpha***	kPa^{-1} or ft^2/lb						x	
van Genuchten SWCC parameter	n_{vG}	***vgn***	Dimensionless						x	
Fredlund and Xing SWCC parameter	a_{vG}	***fxa***	kPa							x
Fredlund and Xing SWCC parameter	n_{FX}	***fxn***	Dimensionless							x
Fredlund and Xing SWCC parameter	m_{FX}	***fxm***	Dimensionless							x
Fredlund and Xing SWCC parameter	ψ_r	***fxr***	kPa							x

3.1.2.2. Layered Material Properties

If the user can represent the subsurface distribution of material properties by a series of layers, Scoops3D can readily accommodate these layers. Scoops3D uses the strength properties of the layer intersected by the trial surface for each column in a potential failure mass to compute stability. Scoops3D vertically integrates the weights of multiple layers, if they exist, to determine the total weight acting on each column base in the potential failure mass.

The user defines the elevation of the lower boundary of each layer by an ASCII raster grid, with each grid contained in a separate file (section 4.4.1.1.4.1). The user must construct these grids using other software, and the grids must exactly match the extent and cell size of the DEM grid. The top of the shallowest layer is the DEM and the bottom of the deepest layer is undefined as it is infinitely deep (fig. 3.1). Layers can be discontinuous, allowing for some regions of the domain to have a subset of the layers. Each layer has its own properties, as listed in table 3.2, that are defined in the main parameter input file. The properties required depend on the groundwater configuration option selected (table 3.2).

3.1.2.3. 3D Properties

Scoops3D can incorporate a full 3D spatial distribution of subsurface properties using a 3D file. This is the most complex option, and the user may need a 3D model (such as a geophysical model) to acquire the 3D distribution. The user will need to format the data in the appropriate file format (section 4.4.2.2). In general, each 3D data point needs an x, y, and z location, as well as material property values for that location. Data must be provided for all DEM cell locations; the vertical depths of the data at each DEM cell can be regularly (constant) or irregularly spaced. If only some of the required parameters listed in table 3.2 vary in the 3D domain, these can be entered in the file and the other parameters can be set to constant values throughout the domain (by defining values in the main input file). The user can select how strength (angle of internal friction and [or] cohesion) is determined at the base of each column on a trial surface from the 3D data; it can be computed either by linearly interpolating between adjacent vertical data points that bracket the base or by using the value within the block containing the base. The 3D properties option cannot be combined with the layered material properties option: it also cannot be used with 3D variably saturated groundwater configurations.

3.1.3. Groundwater Configuration

Scoops3D offers several methods to include the effects of pore-water pressures on slope stability. These options range from no groundwater to pore pressures defined by a piezometric surface or a 3D pore-pressure head field. Cases with no groundwater do not require additional files, whereas piezometric surfaces and 3D distributions of pressure head require additional input files. Only one of the options described below can be selected.

3.1.3.1. None

This option is simple and allows the user to compute slope stability for a landscape with no groundwater pressures. No additional files or parameters are required; the option is selected in the main input file (section 4.4.1.1.3). Only values for total unit weight are used in the slope stability computations.

3.1.3.2. Pore-Pressure Ratio, r_u

This option allows the use of a pore-pressure ratio, r_u, to incorporate the effects of pore-water pressure into the slope stability calculations. This value, proposed by Bishop (1955), is defined as the ratio of pore pressure to vertical stress at a point (section 2.4, equation 2.37); it is widely used in geotechnical analyses. The use of r_u is an easy way to include pore-pressure effects in a stability analysis; however, r_u is unlikely to be constant throughout a hillslope or along a trial surface. Scoops3D allows the user to enter different r_u values for each material layer (if the layer option is selected). No additional input files for r_u are needed. For this option, only values for total unit weight are used in the slope-stability computations.

3.1.3.3. Piezometric Surface

This option allows the user to incorporate a relatively simple 3D distribution of pore pressure by using a piezometric surface that represents the water table with vertically hydrostatic pressure heads beneath the surface. Such an assumption is unlikely to be valid throughout hilly topography but it is widely used in geotechnical analyses and is more conservative (that is, more destabilizing) than a slope-parallel flow field (for example, Reid, 1997). In this option, pore pressure acting on the trial surface of a column is defined by the vertical depth beneath the piezometric surface multiplied by the unit weight of water (section 2.4, equation 2.38). For a column with the trial surface above the piezometric surface, pore pressure is zero. To use this option, the user needs to provide an ASCII raster file containing the elevations of the piezometric surface at each DEM cell location (section 4.4.2.1.5). Values for saturated unit weight, γ_s, are used for the potential failure mass beneath the piezometric surface and partially saturated unit weights, γ_{ps}, are used for mass above the piezometric surface. The total weight of a given column in the potential failure mass is derived from the vertical integration of these components.

3.1.3.4. 3D Pressure Heads

The 3D pressure-head option allows the user to assess the effects of a complex groundwater flow field on slope stability in Scoops3D. The spatial variation in pressure head underlying convoluted topography will likely be complex; thus the user will probably obtain the data from a 3D groundwater flow model (such as the USGS model MODFLOW [Harbaugh and others, 2000]) and modify the data to fit formats acceptable to Scoops3D (see Seattle example, section 7.5). For this option, the user must provide a separate 3D file containing a list of locations with corresponding pressure head, in one of the file formats given in section 4.4.2.2. As with the 3D material properties file, data must be provided for each DEM cell location; the vertical depths of the data at each cell can be regularly (constant) or irregularly spaced. Pore pressure for the stability calculations is computed from pressure heads contained in the file (section 2.4). The pressure value acting on the trial surface of each column is derived by linearly interpolating between adjacent vertical data points that bracket the base of the column. Values for saturated unit weight, γ_s, are used for the potential failure mass with positive pressures heads and partially saturated unit weights, γ_{ps}, are used for mass with non-positive pressure heads. The total weight of a given column in the potential failure mass is derived from the vertical integration of these components. With this option, any negative pressure heads contained in the 3D file are assumed to equal zero in the stability calculations (section 2.4).

3.1.3.5. 3D Variably Saturated Configurations

If the user wants to include the effects of both saturated and partially saturated pore-water pressure on slope stability, Scoops3D can incorporate a 3D distribution of variably saturated pressure head (both negative and positive relative to atmospheric pressure) using one of three approaches (section 2.4). For these approaches, the user will need to provide either: (1) a 3D file containing locations with corresponding variably saturated pressure head and water content, (2) parameters for a van Genuchten soil-water characteristic curve (SWCC) as well as a 3D file containing variably saturated pressure heads, or (3) parameters for a Fredlund and Xing SWCC as well as a 3D file containing variably saturated pressure heads. These approaches can also be used for unsaturated conditions. 3D files should be in one of the formats given in section 4.4.2.2. Typically, a variably saturated groundwater flow model will be needed to obtain a complex distribution of pressure head and (or) water content. If selected, a SWCC can be used to derive water content from a given soil-water suction, thereby eliminating the need for a 3D distribution of water content. In all these approaches, as with the 3D pressure-head option (section 3.1.3.4), pore pressure acting on the trial surface of each column is derived by linearly interpolating between adjacent vertical data points that bracket the base of the column. The total weight of a given column in the potential failure mass is derived from the vertical integration of the unit weights defined by the vertical distribution of water contents (obtained directly from the 3D file or from the SWCC, depending on the option selected). This option cannot be used with a 3D material properties file.

3.1.4. Earthquake Loading

Stability calculations in Scoops3D can include simplistic effects of earthquake or seismic loading in a pseudo-static analysis by adding a specified pseudo-acceleration, k_{eq}. This coefficient scales weight and is applied as a uniform horizontal force, to represent the effects of ground acceleration from an earthquake (Seed, 1973; Chowdhury, 1978). To implement this option, the user defines a horizontal pseudo-acceleration coefficient (dimensionless and scaled as a fraction of gravity, g). The additional horizontal force is applied in the direction of slip and added to the stability calculations for all trial surfaces in the analysis.

3.2. Search of the 3D Domain

To adequately assess the slope stability of all parts of a 3D domain underlying a DEM, Scoops3D must perform a complete search. This section describes the important controls used to define and control the search. Practical considerations for implementing search procedures and assigning search parameters are given in chapter 5.

Scoops3D computes slope stability using limit-equilibrium analysis for a predefined trial surface, as described in section 2.1. Therefore, assessing slope stability throughout the DEM requires determining the stability of a wide variety of trial surfaces at different depths, with all parts of the DEM included in at least some trial surfaces. A thorough search with many trial surfaces is necessary because: (1) the minimum factor of safety needs to be determined for each DEM cell in the digital landscape, and (2) variations in local topography, 3D material properties, and 3D pore-water pressures create opportunities for many local minima in factor of safety. Depending on the search parameters selected by the user, Scoops3D might compute slope stability for thousands to millions of valid trial surfaces intersecting the DEM.

The search process is aided by the requirement that each trial surface is part of a sphere defined by a ***rotational center*** point located above the DEM and a given radius. Using a finite 3D orthogonal array of rotational centers (here called the ***search lattice***, fig. 3.2), Scoops3D can create and analyze multiple trial surfaces, with some surfaces affecting each part of the DEM. This approach is analogous to the grid of rotational centers commonly used to determine a critical potential failure surface in 2D geotechnical analyses (Boutrup and Lovell, 1980; Krahn, 2004). Although other geotechnical software might allow the user to specify that all trial surfaces intersect a specified layer or exit at a specified location, such site-specific controls on stability are typically unknown over a DEM. Therefore, Scoops3D does not provide the user with these options. A spherical failure surface shape is maintained for all trial surfaces; Scoops3D does not attempt to optimize the trial surface shape to determine a minimum factor of safety, as some researchers have done in 2D and 3D (Boutrup and Lovell, 1980; Chen and Shao, 1988; Duncan, 1996; Yamagami and Jiang, 1997; Chen and others, 2001; Zhu, 2001; Jiang and Yamagami, 2004).

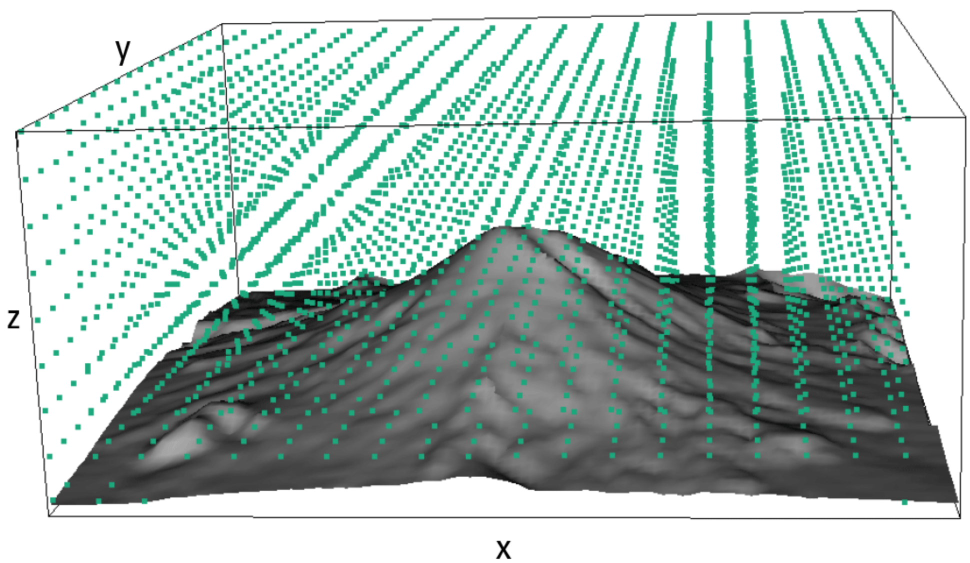


Figure 3.2. Diagram showing a 3D search lattice above a DEM. Each green dot represents the center of multiple spherical trial surfaces.

During the search process, Scoops3D keeps track of the minimum factor of safety computed for each DEM cell, out of all the trial surfaces encompassing that cell. The trial surface with the minimum factor of safety is defined here as the ***critical surface*** for that DEM cell. Scoops3D also retains the size of the potential failure mass associated with that critical surface, called the ***critical size***. When the overall search is complete, Scoops3D produces 2D map-view grids of the minimum factor-of-safety values and associated critical sizes (volume or area depending on user-specified primary size criteria - see section 4.4.1.1.10). The size grids do not portray the complete spatial extent of every critical potential failure mass at a given DEM cell because adjacent DEM cells may have been affected by a different critical surface with a lower factor of safety. Scoops3D also provides an output file containing summary parameters for all the critical surfaces (see section 4.5.1.4). Cells on the boundaries of the DEM that cannot be included in any valid trial surfaces are assigned null values. The main output file lists the trial surface with the overall or ***global minimum F*** value found during the search.

To limit the infinite number of permutations for searching a DEM, Scoops3D allows the user to select some search restrictions. These options include: (1) conducting a search using a rectangular box-like search grid aligned with the DEM (Box search option), (2) analyzing a single, user-selected trial surface (Single surface option), or (3) performing a variant of a box search constrained by lateral limits defined in a file (File search option). Details of the input parameters for each option are presented in section 4.4.1.1.9. Practical considerations for constructing a thorough search are discussed in chapter 5.

For a box or file search, the user can elect to perform either a *simple search* or a *coarse-to-fine search*. Although the simple search option can provide the most thorough search, it can be quite time-consuming and is typically unnecessary. The coarse-to-fine search method greatly reduces computational effort, commonly reducing run times by as much as 90 percent. These options are described in the following sections.

3.2.1. Simple Box Search

A simple box search in Scoops3D (fig. 3.2) analyzes spherical trial surfaces generated with a rotational center at each node in the search lattice, and then proceeds to analyze trial surfaces generated at the next node in the search lattice in a systematic fashion until all nodes have been searched. Thus, to perform a thorough search of a digital landscape, the user must define the lateral and vertical extent and resolution (node spacing) of the 3D search lattice (details are given in section 4.4.1.1.9.1). Table 3.3 lists the user-defined parameters that control a simple box search.

Table 3.3. List of user-specified parameters required for simple box searches.

[Details can be found in section 4.4.1.1.9.1. Note that these parameters can be readily selected and adjusted in the Search Configuration window found in the user interface program, Scoops3D-i (section 4.3.3.5)]

Parameter name	Controls	Comments
A. Size criteria		
vacriterion	Primary size criterion	Can be volume or area
armin or vmin	Minimum size	In units of primary size criterion
armax or vmax	Maximum size	In units of primary size criterion
tol	Size tolerance	In units of primary size criterion
dr	Radius increment	In length units of DEM
B. Slip directions		
numdir	Number of directions	Odd integer required
degmax	Maximum deviation from fall	Degrees
deginc	Interval size	Degrees
C. Vertical extent		
zsmin	Minimum z	In length units of DEM
zsmax	Maximum z	In length units of DEM
zsrchres	Vertical resolution	In length units of DEM
D. Horizontal extent		
ismin	Minimum i	x-direction, DEM cell counter
ismax	Maximum i	x-direction, DEM cell counter
jsmin	Minimum j	y-direction, DEM cell counter
jsmax	Maximum j	y-direction, DEM cell counter
nsrchres	Horizontal multiplier	Search every n^{th} horizontal node

There are an infinite number of trial surfaces in the domain beneath a DEM; Scoops3D therefore utilizes size limits (volume and [or] area) defined by the user to constrain the size of potential failure masses. Users are typically interested in the potential stability of masses in a certain size range, rather than those that are comparatively very small or very large. Defining appropriate potential failure size limits is crucial to a satisfactory stability analysis of the entire DEM (section 5.3.2). Scoops3D has two limits for valid potential failure masses: a volume range and a horizontal (planimetric) surface area range (details are given in section 4.4.1.1.10). One or both of these criteria can be used to check for valid trial surfaces, but the user selects one as the primary criterion. Note that the graphical user interface, Scoops3D-i, allows the use of only one (volume or area) size criterion.

At each node in the search lattice there is an infinite number of possible spherical trial surfaces centered on that node. Scoops3D first identifies a surface that creates a potential failure size (either volume or area) near the minimum limit of the primary size criterion, within a tolerance chosen by the user. If the optional secondary criterion is chosen, valid potential failure masses must also have sizes within the minimum and maximum limits of the secondary criterion. Scoops3D then generates and analyzes additional trial surfaces by systematically increasing the radius of rotation in discrete steps, until the potential failure size exceeds the user-selected maximum volume and (or) area limits. Each of these spherical surfaces might intersect the DEM in multiple locations, and thus create multiple subsets of trial surfaces (fig. 3.3). Scoops3D keeps track of as many as ten subsets for each radius and independently analyzes all subsets that meet the volume/area size limits. Scoops3D moves on to the next search-lattice node once the largest subset reaches the user-defined maximum size limit.

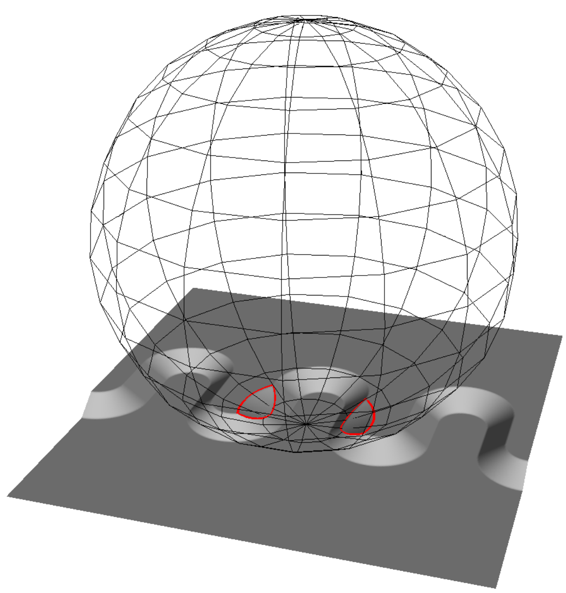


Figure 3.3. Diagram showing a single sphere that intersects an undulating DEM in multiple locations, thereby creating multiple trial surfaces (outlined in red). Scoops3D analyzes each trial surface separately.

Each spherical trial surface can slip (rotate) in any direction, and the computed stability may be different depending on the slip direction. Scoops3D always computes stability in the direction of an overall ground-surface fall direction (defined as the average ground-surface slope direction of all the full-column DEM cells included in a trial mass); this is the default mode. Commonly, this direction provides the minimum factor of safety, but not always. The user can specify that Scoops3D also compute a factor of safety for other slip directions on either side of the overall fall direction. Note that the axis of rotation will change orientation depending on slip direction. Details of specifying these other slip directions are given in section 4.4.1.1.9.1.

3.2.2. Coarse-to-Fine Box Search

For most projects, the user will want to use the coarse-to-fine search option to reduce overall computation time. Although the basic, simple box search described previously systematically examines all nodes in the 3D search-lattice array, this process can be very inefficient, because many of the search-lattice nodes will not yield critical surfaces in the DEM. The refinement technique in the coarse-to-fine search implements a series of iterations, each using a finer-resolution search lattice. The procedure for varying the potential failure mass size and slip direction at every search node is the same as for a simple box search (section 3.2.1).

To use this technique, the user first defines the limits and spacing of the finest search lattice; this serves as the ultimate or final resolution of the search lattice. Then, the user selects a multiplier to create the coarsest resolution lattice subset from the finer lattice (fig. 3.4); this serves as the initial resolution of the search lattice. These additional parameters are listed in table 3.4. Scoops3D first searches all nodes from the coarse initial lattice (fig. 3.4*A*) and identifies the lattice nodes associated with a critical surface (having the lowest factor of safety) for each cell in the DEM (here called a ***critical lattice node*** or ***critical node***).

Table 3.4. List of parameters, in addition to those listed in table 3.3, required for a coarse-to-fine box search.

[Details can be found in section 4.4.1.1.9.1]

Parameter name	Controls	Comments
irefine	Flag to specify coarse-to-fine search	
multres	Initial coarse lattice multiplier	
fostol	*F* tolerance	Value in percent, halts fine search

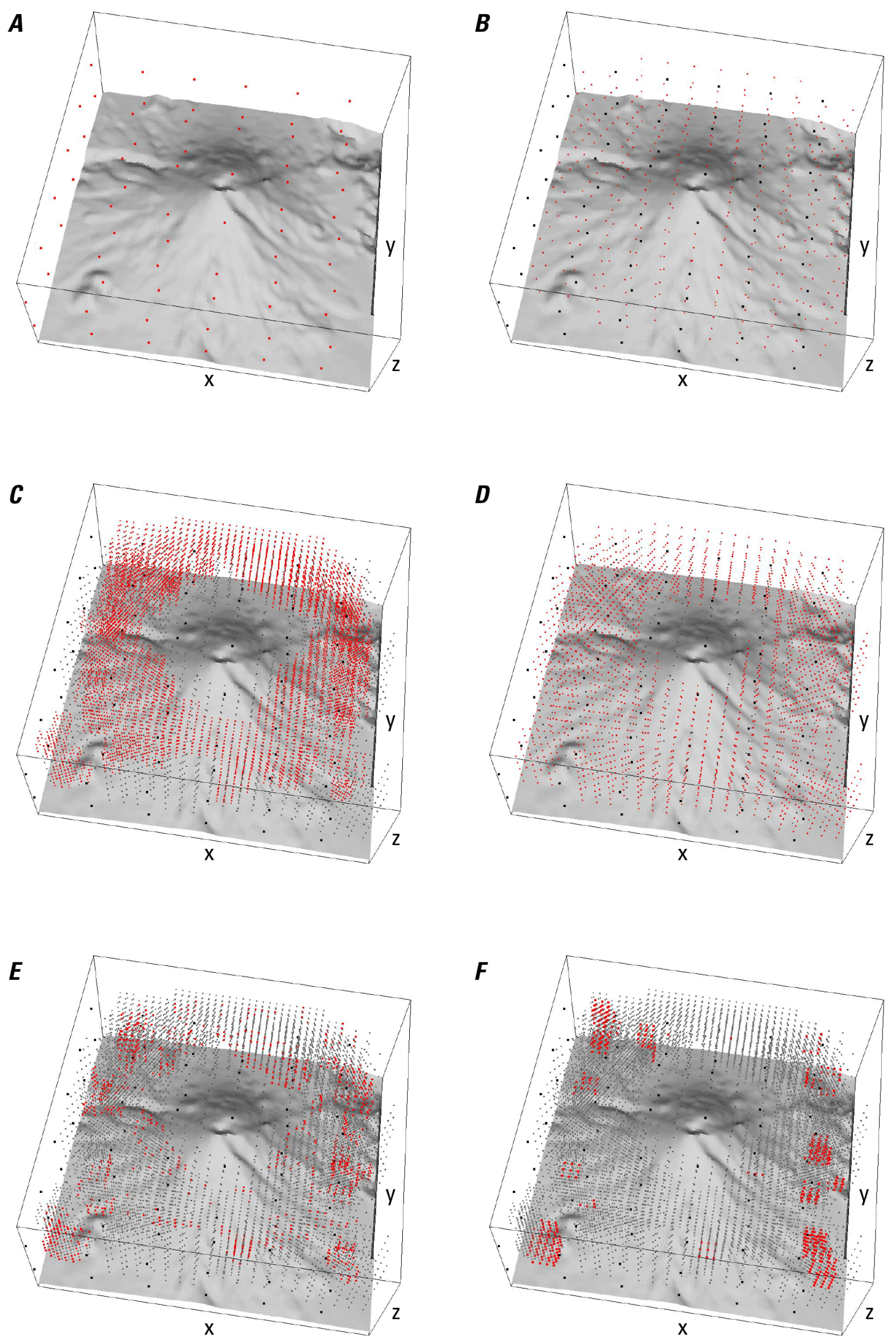


Figure 3.4. Sequence of perspective views (looking down from above) of a DEM and 3D array of search-lattice nodes for a progressive coarse-to-fine search. This example uses a coarse-to-fine multiplier of 8 (***multres*** = 8). *A,* Search-lattice nodes for initial coarse search; overall extent of search is defined by box. *B-F,* Sequence of five iterative searches showing search nodes for a given iteration (red points) and all nodes previously searched (black points). With each iteration, the region containing critical lattice nodes becomes a smaller part of the overall search space.

The critical lattice nodes from this coarse search provide “seeds” for the first refined search iteration, where Scoops3D uses a finer resolution search-lattice interval around each critical node in a box-like region of lattice nodes spaced half the distance between the coarse nodes (fig. 3.4*B*). If any of the finer-resolution nodes have critical surfaces with a lower factor of safety at any DEM cell, that search node becomes a new critical seed node. Subsequent refinements of the search grid (fig. 3.4*C, D, E, F*) use the seed nodes from the previous iteration and search the box with nodes spaced half the distance between nodes used in the previous iteration, thus progressively searching finer and finer resolution lattices around the seed nodes. If no lattice node exists exactly at the halfway location, the next closest node toward the seed node is used instead. The search halts when no finer-spaced nodes result in a valid trial surface with a lower factor of safety than found previously (within a user-defined tolerance, see section 4.4.1.1.9.1), or the search has examined the ultimate fine-resolution lattice. The locations of the critical lattice nodes may shift during the iteration process, but in the end the locations are usually similar to those found in a more complete simple search.

The difference in searched lattice nodes between a simple search and a coarse-to-fine search can be seen by comparing figures 3.2 and 3.4*F*. Our empirical tests show that a multiplier of 6 or 8 for the initial coarse lattice often minimizes the number of trial surfaces examined, as well as the overall run-time, while not significantly compromising the thoroughness of the search. The default settings in Scoops3D-i use a coarse-to-fine search with the coarse grid 8X the spacing of the ultimate fine grid.

Chapter 4. Program Operation

This chapter provides information about installing and running the two software programs, Scoops3D-i and Scoops3D. It describes how to use the graphical user interface (GUI), Scoops3D-i, to easily create and run slope-stability analyses with Scoops3D. It also provides detailed descriptions of the input files and parameters as well as the standard and optional output files.

4.1. System Requirements and Installation

The latest version of Scoops3D, Scoops3D-i, and associated documentation is available for download on the over the Internet at: http://pubs.usgs.gov/tm/14/a01. Consult the ReadMeScoops3D.txt file on this USGS web site for the latest information. The easiest method for installation of Scoops3D is to use the system-specific installation package. Packages are available for Microsoft Windows and Apple Macintosh operating systems to install executable versions of Scoops3D and Scoops3D-i, the Scoops3D manual, as well as associated icons and directories. To install Scoops3D and Scoops3D-i, the user should log in as an administrator (or authenticate as one when requested during the installation process), download the appropriate installer file (for Windows or Macintosh), launch the installer, and follow the directions. Note that the software is not copyrighted and the license agreement is for informational purposes only.

Files containing examples of Scoops3D input and output can be downloaded to the user's directory of choice. Scoops3D can be uninstalled with the Windows uninstaller, or by dragging the Scoops3D folder to the trash on the Macintosh OS.

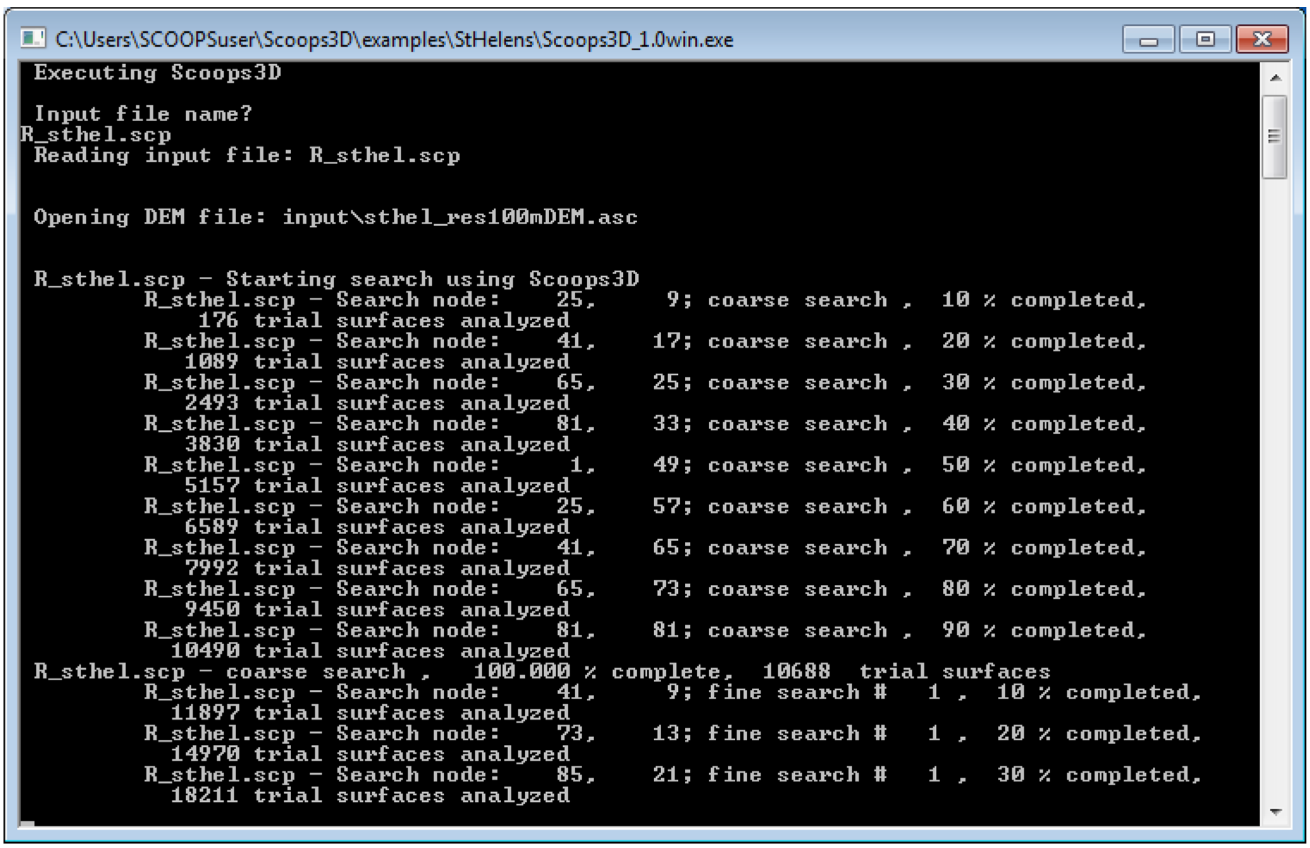
Source code and compiled executable versions of Scoops3D for Windows, Mac, Unix**,** and Linux are also available for download (see the ReadMeScoops3D.txt file for details). Compiled versions of Scoops3D can be executed without the Scoops3D-i interface. Scoops3D is written in the Fortran 90 programming language to provide computational efficiency, dynamic memory management, and cross-platform compatibility. The source code for Scoops3D can be compiled to execute on the user's computer, provided the user has a Fortran 90 language compiler. Thus, users may compile Scoops3D for execution on a wide variety of computer operating systems. We have successfully run versions of Scoops3D on a variety of Windows, Macintosh, Unix, and Linux operating systems - see the ReadMe file on the USGS web site for a current list.

4.2. Running Scoops3D

Scoops3D can be run from either the graphical user interface, Scoops3D-i (section 4.3), or from a command line. Before executing Scoops3D, the user must always construct the main parameter input file and provide a DEM file. Some slope-stability analyses may require additional input files (see section 4.4.2).

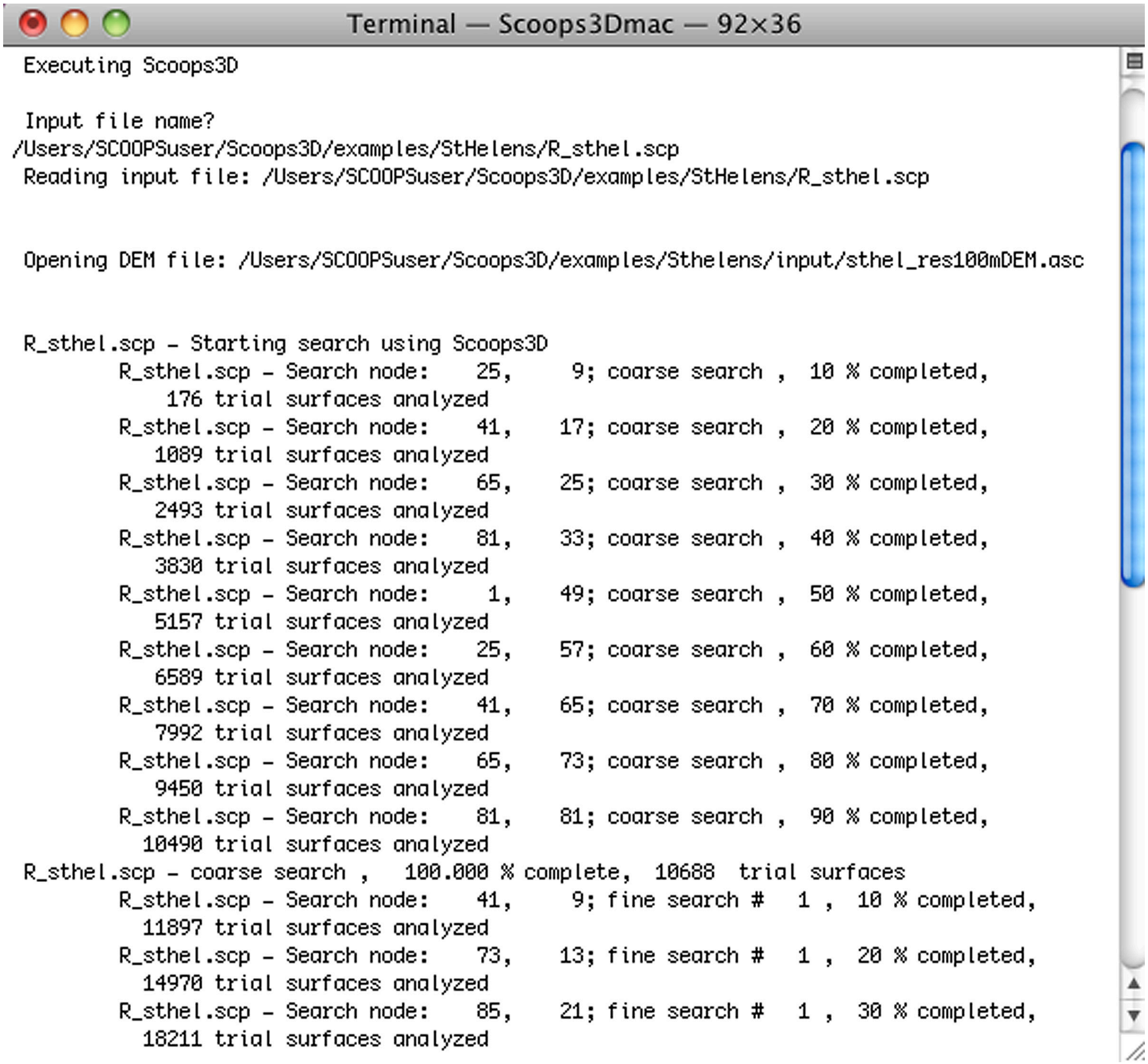
Scoops3D-i provides a convenient tool to readily construct an internally consistent and complete main parameter input file and then to execute one or more Scoops3D runs.

Alternatively, Scoops3D can be executed by double clicking on the Scoops3D executable program icon, or by typing the name of the executable file in a command prompt (Windows) or terminal (Macintosh) window. Before running Scoops3D in this scenario, the user needs to construct a complete main parameter input file (section 4.4.1) using a text editor or Scoops3D-i, as well as provide a DEM file and any necessary additional input files (section 4.4.2). Scoops3D will run and ask for the name of the main parameter input file. After the user enters this file name, Scoops3D executes and displays ongoing screen output (showing the search progress) in the command window. Some examples of command line input are shown in figure 4.1. When Scoops3D has completed execution, a message displays in the command window. In Windows, if the user initiates Scoops3D by double clicking on program icon, the command window will close automatically after Scoops3D completes its execution.



A. Command prompt window in Windows 7.

Figure 4.1. Screenshots showing examples of Scoops3D run from command line input.



```
Terminal — Scoops3Dmac — 92×36
 Executing Scoops3D

 Input file name?
/Users/SCOOPSuser/Scoops3D/examples/StHelens/R_sthel.scp
 Reading input file: /Users/SCOOPSuser/Scoops3D/examples/StHelens/R_sthel.scp


 Opening DEM file: /Users/SCOOPSuser/Scoops3D/examples/Sthelens/input/sthel_res100mDEM.asc


 R_sthel.scp - Starting search using Scoops3D
        R_sthel.scp - Search node:    25,     9; coarse search ,  10 % completed,
            176 trial surfaces analyzed
        R_sthel.scp - Search node:    41,    17; coarse search ,  20 % completed,
           1089 trial surfaces analyzed
        R_sthel.scp - Search node:    65,    25; coarse search ,  30 % completed,
           2493 trial surfaces analyzed
        R_sthel.scp - Search node:    81,    33; coarse search ,  40 % completed,
           3830 trial surfaces analyzed
        R_sthel.scp - Search node:     1,    49; coarse search ,  50 % completed,
           5157 trial surfaces analyzed
        R_sthel.scp - Search node:    25,    57; coarse search ,  60 % completed,
           6589 trial surfaces analyzed
        R_sthel.scp - Search node:    41,    65; coarse search ,  70 % completed,
           7992 trial surfaces analyzed
        R_sthel.scp - Search node:    65,    73; coarse search ,  80 % completed,
           9450 trial surfaces analyzed
        R_sthel.scp - Search node:    81,    81; coarse search ,  90 % completed,
          10490 trial surfaces analyzed
 R_sthel.scp - coarse search ,   100.000 % complete,  10688  trial surfaces
        R_sthel.scp - Search node:    41,     9; fine search #   1 ,  10 % completed,
          11897 trial surfaces analyzed
        R_sthel.scp - Search node:    73,    13; fine search #   1 ,  20 % completed,
          14970 trial surfaces analyzed
        R_sthel.scp - Search node:    85,    21; fine search #   1 ,  30 % completed,
          18211 trial surfaces analyzed
```

B. Terminal window in Mac OS 10.6.

Figure 4.1. —Continued

4.3. Using Scoops3D-i, the Graphical User Interface

The graphical user interface (GUI) for Scoops3D, called Scoops3D-i, provides a convenient way to create and (or) modify the main parameter input file needed to run Scoops3D. Scoops3D-i can also perform tasks such as running or stopping Scoops3D. By using Scoops3D-i, the user can create a complete and internally consistent input file. Once completed, this main parameter input file provides a listing of paths to all additional input files (such as files containing the DEM, subsurface distributions of material properties, or groundwater conditions) required for a given stability assessment. Scoops3D-i does not construct these additional input files – they must be prepared using other software. A complete listing of input files required by Scoops3D to perform various slope-stability assessments is presented in section 4.4.

4.3.1. Basic Tasks with Scoops3D-i

Scoops3D-i enables the user to perform the following activities:

- Create a new main parameter input file for Scoops3D.
- View and (or) modify an existing Scoops3D parameter input file.
- Create a new parameter input file for Scoops3D using a trial surface from a previous Scoops3D run.
- Check a Scoops3D input file for completeness before running.
- Run Scoops3D with a designated input file.
- Stop a Scoops3D run in progress.
- Create additional parameter input files and run multiple Scoops3D runs at the same time.
- View the text-based input and output files from a Scoops3D run.
- Delete the output files from a previous Scoops3D run.

4.3.2. Getting Started with Scoops3D-i

Locate and launch the Scoops3D-i application using procedures appropriate for your computer operating system (such as double-clicking on the Scoops3D-i icon). After Scoops3D-i briefly displays a banner, the main window with a menu bar opens (fig. 4.2), along with an additional command line window (in the Windows operating system) to display runtime messages from Scoops3D-i and Scoops3D. Both windows close when Scoops3D-i is terminated. The user can perform basic tasks (see section 4.3.1) through the main Scoops3D-i window. This window contains a form for creating a Scoops3D input file as well as a menu bar with choices for modifying the input file and running Scoops3D. The main window pull-down menus are listed under **File, Edit, View, Run, Options**, and **Help**. The Scoops3D-i program can be terminated by selecting **File** > **Quit** or clicking the close button of the window.

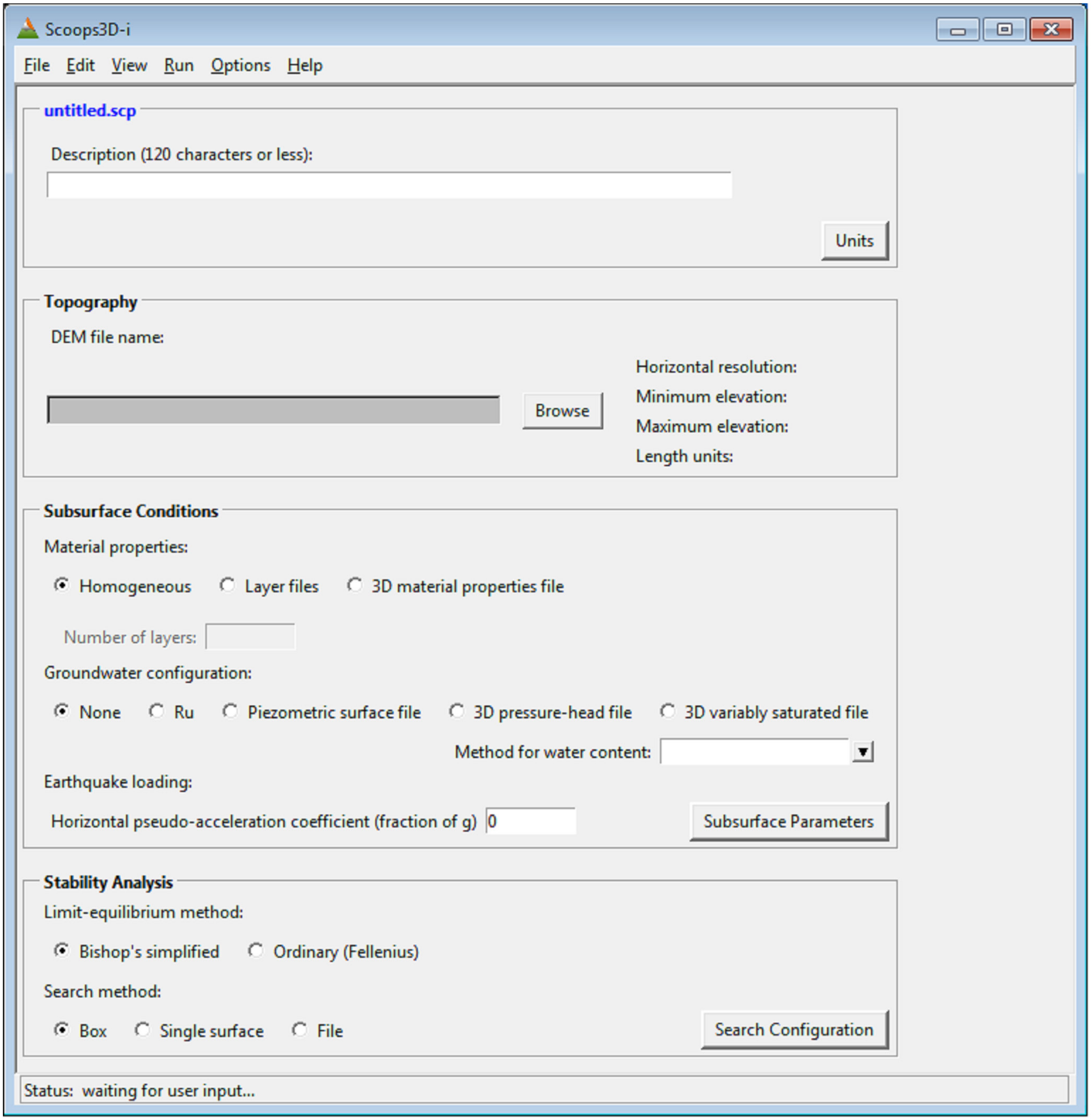


Figure 4.2. Screenshot showing the main Scoops3D-i window with default parameters and main menu bar.

4.3.3. Create a New Input File for Scoops3D

The main parameter input file for Scoops3D can be readily constructed using the main window (fig. 4.2) and associated "child windows" in Scoops3D-i. When Scoops3D-i first opens the main window or child windows, the windows contain a combination of blank parameters and default values. Selecting **File > New** in the main window menu bar resets the windows to these initial values. Child windows are accessed by way of buttons in the main window and are used for entering additional information. If desired, a main parameter input file can be saved in a partially complete state (by selecting **File > Save** or **File > Save As** in the main window menu bar) and reopened later for further modification. Scoops3D-i creates and prefers main parameter input files with a .scp extension.

Detailed descriptions of each input parameter are provided in section 4.4.1, and are briefly summarized here. Input parameter names (for cross-referencing with section 4.4.1 descriptions) can be obtained by selecting **Help** > **Balloon Help** in the main window menu bar and then hovering with the cursor over an input area or radio button. In addition, brief descriptions of each variable can be viewed in a separate window by selecting **Help > Scoops3D Variable Descriptions**.

The main Scoops3D-i window contains four sections for defining input parameters (fig. 4.2). Parameters can be selected in any order, but it is often useful to start at the top of the form and work down. Some default values for select parameters are based on other parameters (for example, the default horizontal extent of a box search is set by the dimensions of the DEM, thus entering the DEM first enables these default extents to be computed). The interface also restricts some parameters to an appropriate data type (for example, an integer, numeric, or character) and (or) an appropriate range of values. By following the sequence of entries described below, Scoops3D-i can be used to create a complete and consistent main parameter input file.

4.3.3.1. Description and Units

The top section of the main Scoops3D-i window displays the main parameter input file name (this name is **untitled.scp** if the file has not been saved already), a file description (as many as 120 characters), and a button for selecting unit descriptors. Clicking this button brings up the window shown in figure 4.3. The user can select the appropriate system of units for length, unit weight, and cohesion. Note that Scoops3D does not perform any unit conversions; the user should enter parameters in appropriate and consistent units (see section 4.4.1.1.2) and length units should match those of the DEM. Click **OK** or **Cancel** to return to the main window; values in the main window cannot be changed while a child window is open.

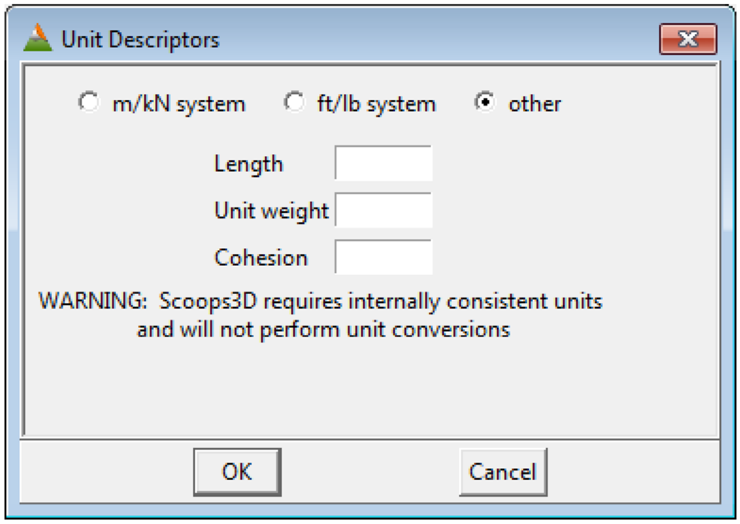


Figure 4.3. Screenshot showing window in Scoops3D-i for defining unit descriptors.

4.3.3.2. Topography

The second section in the main window allows selection of the DEM (digital elevation model) file using the **Browse** button. **Note that the name must be selected by browsing rather than typed in directly.** As a default the browse window displays files with .asc extensions (see section 4.4.2.1 for a description of the DEM file format). Once the DEM file is selected, the filename as well as the horizontal resolution and maximum and minimum elevations appear in the main window. **Length units are displayed based on the unit descriptor selected previously**; they are not read from the DEM file itself.

4.3.3.3. Subsurface Conditions

The third section in the main Scoops3D-i window contains information about subsurface conditions, including material properties, groundwater configuration, and earthquake loading. Material properties (strengths and unit weights) underlying the DEM can be characterized using homogeneous values, layers with differing properties (with layer elevations defined in a series of separate .asc files), or a 3D properties file. Depending on the desired configuration, select the appropriate **Material properties** option. If the layer files option is selected, enter the number of layers. Next, select a **Groundwater configuration** option: none (dry), Ru (pore-pressure ratio), piezometric surface file (.asc grid file containing water table elevations), a 3D pressure-head file, or a 3D variably saturated configuration. If the latter option is chosen, also select an option, either 3D combined water content file, van Genuchten SWCC, or Fredlund and Xing SWCC, from the pull-down menu. If earthquake loading is included, enter the dimensionless horizontal pseudo-acceleration coefficient (scaled as a fraction of g). If no earthquake loading effects are desired, leave this value set to zero.

After selecting options for these conditions, the user must click the **Subsurface Parameters** button to further define parameters based on the options selected in the main window. Failure to complete the **Subsurface Parameters** child window results in an incomplete input file. The **Subsurface Parameters** window that appears when the **Subsurface Parameters** button is clicked depends on which of the many possible combinations of material properties and groundwater configurations has been selected. Here we discuss three examples with increasing complexity. The simplest configuration (homogeneous with no groundwater) is shown in figure 4.4. For this case, enter cohesion, angle of internal friction, and total unit weight of the homogeneous material. A more complicated configuration (three material layers with a piezometric surface file) is shown in figure 4.5. In this case, the prefix (or root file name) for the layer files is defined using the upper **Browse** button and selecting any one of the layer files. **Note that layer files are required to have a common prefix** (section 4.4.2.1.4). Scoops3D-i extracts the prefix from the selected layer file. Next, enter cohesion, friction angle, and the partially saturated and saturated unit weights for all three layers, as well as the unit weight of water. Finally, select the piezometric surface file using the lower **Browse** button. Both layer files and piezometric surface files must be in .asc grid format (section 4.4.2). Click **OK** when finished to return to the main window. Clicking **Cancel** returns to the main window without making changes.

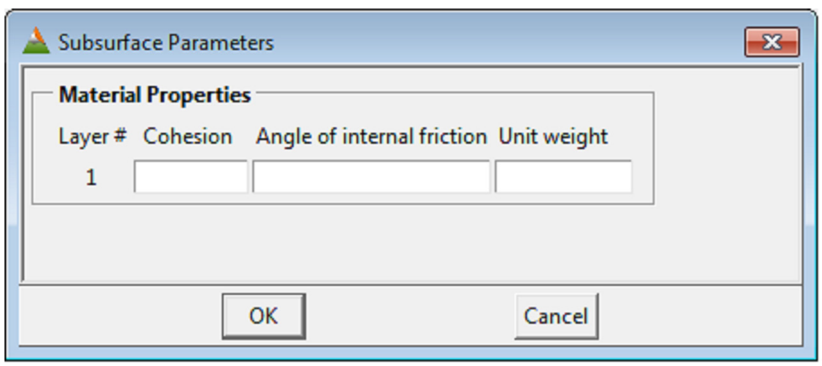


Figure 4.4. Screenshot showing window in Scoops3D-i for defining subsurface parameters when homogeneous material properties and no groundwater options are selected.

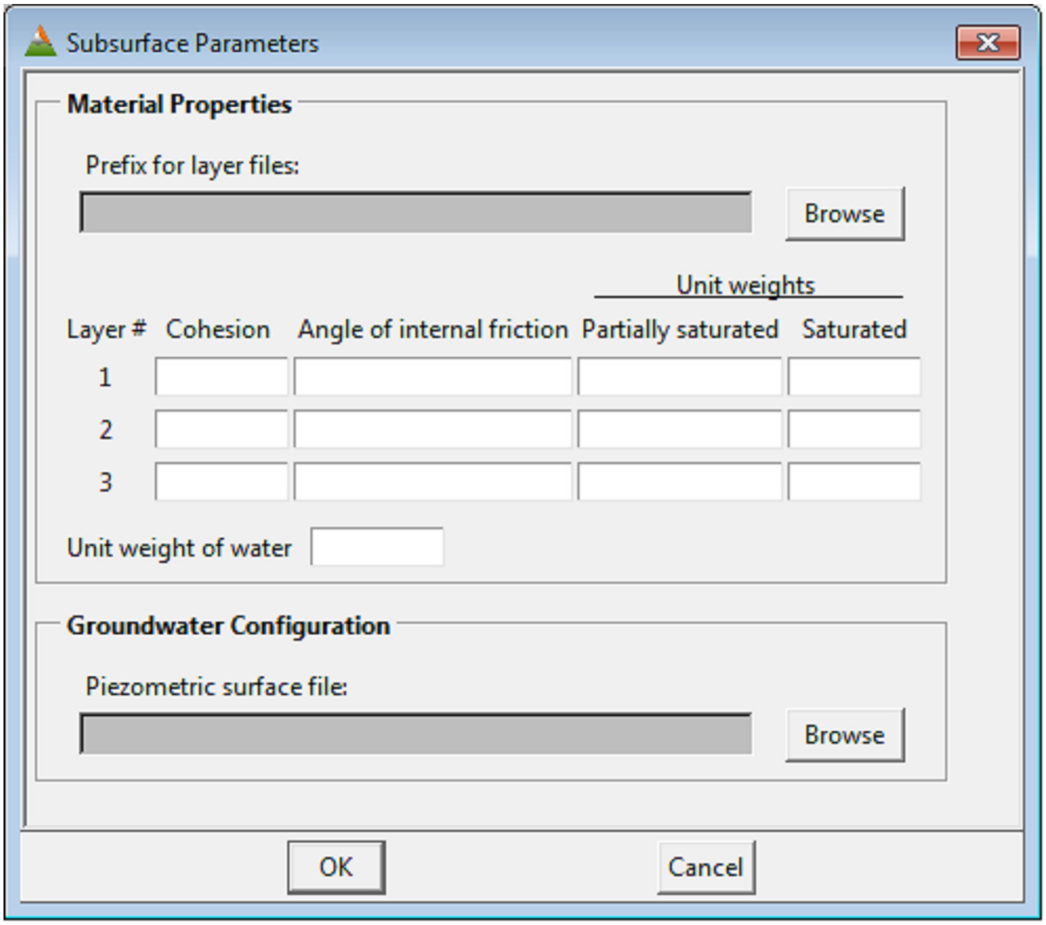


Figure 4.5. Screenshot showing window in Scoops3D-i for defining subsurface parameters when three layers and a piezometric surface file are selected.

An even more complex configuration (3D material properties file with 3D pressure-head file) is shown in figure 4.6. Here, click the upper **Browse** button to select a 3D material properties file (with a default .txt extension). Then select a method for defining the vertical distribution of values, either using linear interpolation between points or defined blocks with fixed parameter values. Select which parameters (cohesion, angle of internal friction, partially saturated, and [or] saturated unit weights) have a 3D distribution contained in the 3D file. At least one, and up to all, of the parameters may be defined in the file – ensure that the appropriate parameters are selected. For parameters not contained in the 3D file, enter values in the Layer #1 non-grey boxes. These values are assumed to be uniform throughout the 3D domain. Also, enter the unit weight of water in units consistent with the other unit weights. Finally, click the lower **Browse** button to select the 3D pressure-head file (with a default .txt extension). Click **OK** when finished to return to the main window.

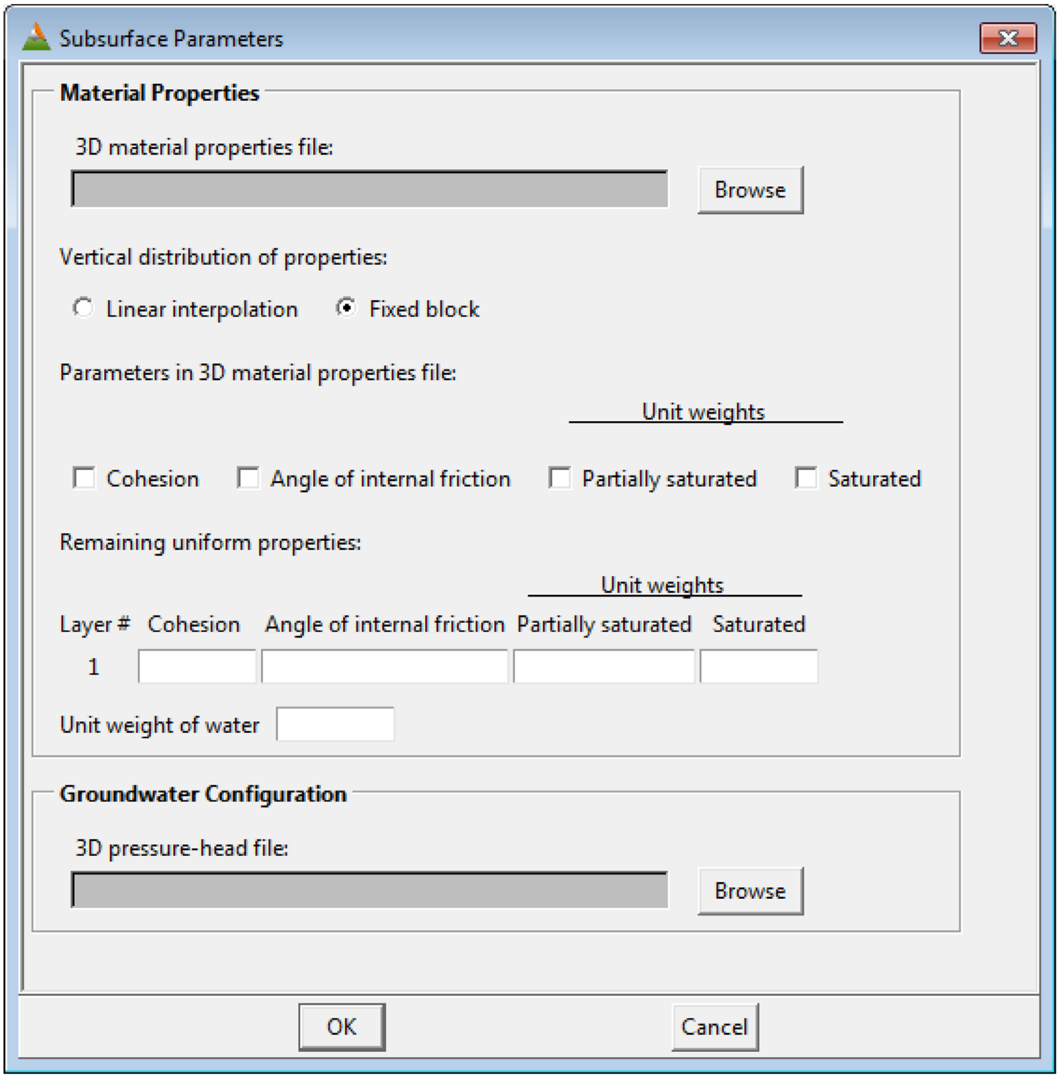


Figure 4.6. Screenshot showing window in Scoops3D-i for defining subsurface parameters when 3D material properties and 3D pressure-head file options are selected.

4.3.3.4. Stability Analysis: Limit-Equilibrium Method

The fourth section of the main window contains options for the limit-equilibrium method and search method. Select either the Bishop's simplified or Ordinary (Fellenius) methods (see section 2.3 for a description of these methods). Typically Bishop's method produces slightly more accurate factor-of-safety results, although the Ordinary method provides a reasonable result in some cases where Bishop's method produces spurious results (section 5.3.7). An advanced option when using Bishop's method allows filtering of trial surfaces with spurious factors of safety (that is, those that have a small absolute value of m_α, see section 2.3.2) from the results. The value for this filter is adjusted by selecting **Options > Advanced Parameters** from the main window menu bar. See section 4.4.1.1.8 for a more complete description of this option.

4.3.3.5. Stability Analysis: Search Method

Three methods are available to define the search lattice above the DEM: searching a box shaped lattice, computing a single trial surface using one lattice node, or searching a lattice region with the horizontal extent defined in a file (this can allow a non-rectangular horizontal extent of the search lattice). After selecting an option, the user must click the **Search Configuration** button to further define search parameters based on the option selected in the main window. An incomplete **Search Configuration** child window produces an incomplete input file. Selecting appropriate search parameters is crucial to performing a thorough search and completely mapping the factors of safety throughout the DEM. Some trial and error runs with different settings can help determine whether a thorough search has been performed (see chapter 5). See section 3.2 for further explanation of the search methods.

4.3.3.5.1. Box Search

If the box search method is selected and the user clicks the **Search Configuration** button, a window similar to that shown in figure 4.7 appears. The box option is the standard search method in Scoops3D. The top section of the window requires specification of the criterion for limiting the size range of potential failure masses. The range limits are based on either potential failure areas (horizontal extent) or volumes. Minimum and maximum values must be entered. It is usually not possible for Scoops3D to define an initial surface that exactly matches the minimum selected; thus a tolerance (as a percentage of the minimum value) is needed to obtain a trial failure with a size that falls within the range between the minimum and the minimum plus tolerance. The default tolerance is 10 percent of the minimum size. Smaller tolerance values force Scoops3D to obtain an initial trial surface with a size closer to the minimum, but can result in additional computational effort.

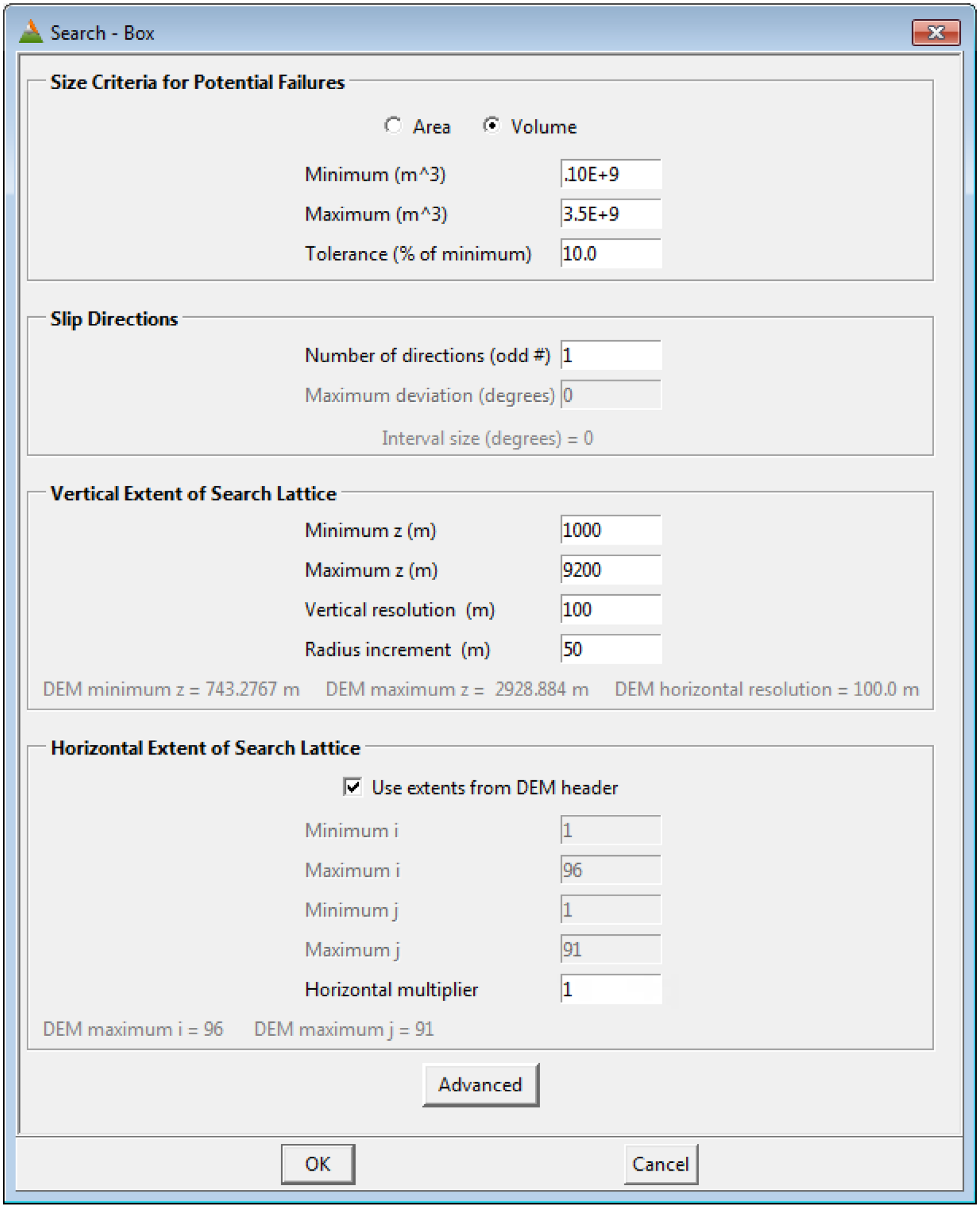


Figure 4.7. Screenshot showing window in Scoops3D-i for defining search configuration parameters for the box search method. This window shows parameters specified for Scoops3D Mount St. Helens example R (parameter file: *R_sthel.scp*) described in section 7.6.

The second section of the window (**Slip Directions**) defines the number of slip directions and the maximum range of angles to analyze for each trial surface. The range is defined as the maximum deviation on either side of the slip direction obtained from the overall fall direction for the potential failure mass. Because the slip surface is spherical, a potential failure may occur with rotation in any direction. Scoops3D can compute the factor of safety for any rotation direction, but it always analyzes the case in the direction defined by the overall fall direction (see section 2.2). If the number of directions selected is one, then the factor of safety is computed only in the overall fall direction. If the number of directions is greater than one, then additional factors of safety are computed for slip directions on either side of the overall fall direction. Maximum deviation on either side of the fall direction is defined as an angle in degrees. Scoops3D-i computes the degree increment as a function of the number of slip directions and the maximum deviation to either side of the overall fall direction.

The third section of the **Search - Box** window (**Vertical Extent**) defines the minimum and maximum vertical (z) extent of the search box in length units of the DEM – **these are elevation values not relative vertical distances.** The minimum z value should be greater than the lowest DEM elevation. An appropriate maximum z value may need to be determined by trial and error – it should be large enough to find minimum factor of safety values for all parts of the DEM, yet not large enough to cause unneeded computations (section 5.3.5). The vertical resolution is the distance between evenly spaced search-lattice nodes in the z direction, **in length units of the DEM**. The radius increment is also defined in length units of the DEM and represents the radius length increment for the set of spheres analyzed at a given lattice node; valid spheres must produce potential failure masses between the selected minimum and maximum sizes.

The fourth section in this window (**Horizontal Extent**) defines the horizontal extent of the search box; here units are index counters defined relative to center of the lower left cell of the DEM, which corresponds to the coordinates i = 1, j = 1. Values of i increase in the positive x direction and j increase in the positive y direction (fig. 4.17). Minimum and maximum i and j values define the horizontal extent of the search lattice. A common choice is to define the horizontal search extent to match the extent of the DEM - the box at the top of the **Horizontal Extent** section can be checked to automatically create i and j limits that match the DEM. To search a box that includes search-lattice nodes outside the horizontal extent of the DEM, minimum i and j values can be set to negative values (each increment or decrement represents one additional DEM cell spacing) and maximum i and j values can be set to values greater than those defining the extent of the DEM. Alternatively, for a search box smaller than the DEM extent, the minimum i and j values should be greater than one, and the maximum i and j values less than the values defining the extent of the DEM (see section 4.4.1.1.9.1). The horizontal multiplier allows the search-lattice nodes to be defined at multiples of the DEM cell size. For example, a value of 2 places lattice nodes over the center of every other DEM cell. Note that the search-lattice nodes are located at the center of the DEM cells. See section 3.2 for further description of the search methods.

Clicking the **Advanced** button brings up the window shown in figure 4.8. This allows the user to select a simple search (where all lattice nodes are searched) or a coarse-to-fine search (section 4.4.1.1.9.1). Typically a coarse-to-fine search provides the most computationally efficient search, although a simple search may provide a more thorough examination. We have found empirically that a multiplier of 8 and a tolerance of 0.01 percent (the default values) produce a reasonably thorough yet computationally efficient search. Checking the box at the top of the window restores these default values if they have been modified. Click **OK** when finished to retain the selected parameters and return to the main window.

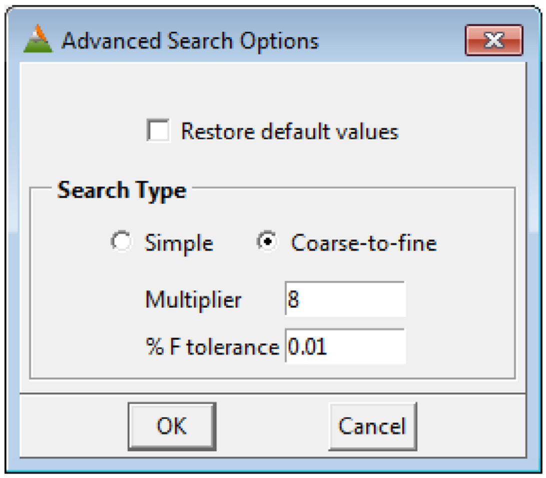


Figure 4.8. Screenshot showing window in Scoops3D-i for selecting advanced search options.

4.3.3.5.2. Single Trial Surface

Scoops3D can compute the factor of safety for a single trial surface. This option is not a search; instead it relies on selecting one trial surface from a pre-existing search or precisely specifying the coordinates of one trial sphere. Selection of this option opens the window in figure 4.9 (if the user has already selected a DEM file). Select either **Pre-existing run** (this allows the user to select a single surface from a previous Scoops3D run) or **Enter manually** (this allows the user to precisely define a single surface). If **Pre-existing run** is selected and **Next** is clicked, then the window shown in figure 4.10 opens. Selecting a single surface from a pre-existing run allows the user to readily obtain the factor of safety, *F*, and volume information about individual trial surfaces from a previous search. Click on the **Browse** button to select a pre-existing Scoops3D input file. Output files associated with this input file must already exist. Possible selections from a pre-existing run include: the single surface with the global minimum *F* for the entire DEM, the single surface having the largest volume with *F* less than some chosen cutoff value, and the single surface having the lowest *F* at a specified location in the DEM. The x- and y-coordinates for this latter selection are specified in the coordinate system of the DEM (see section 4.4.2.1). Click **OK** when finished to return to the main window.

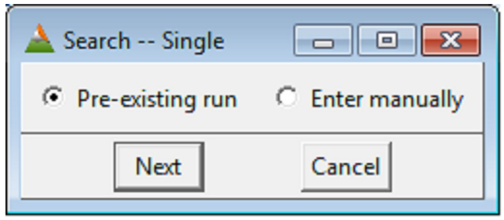


Figure 4.9. Screenshot showing window in Scoops3D-i for selecting the method to define a single trial surface.

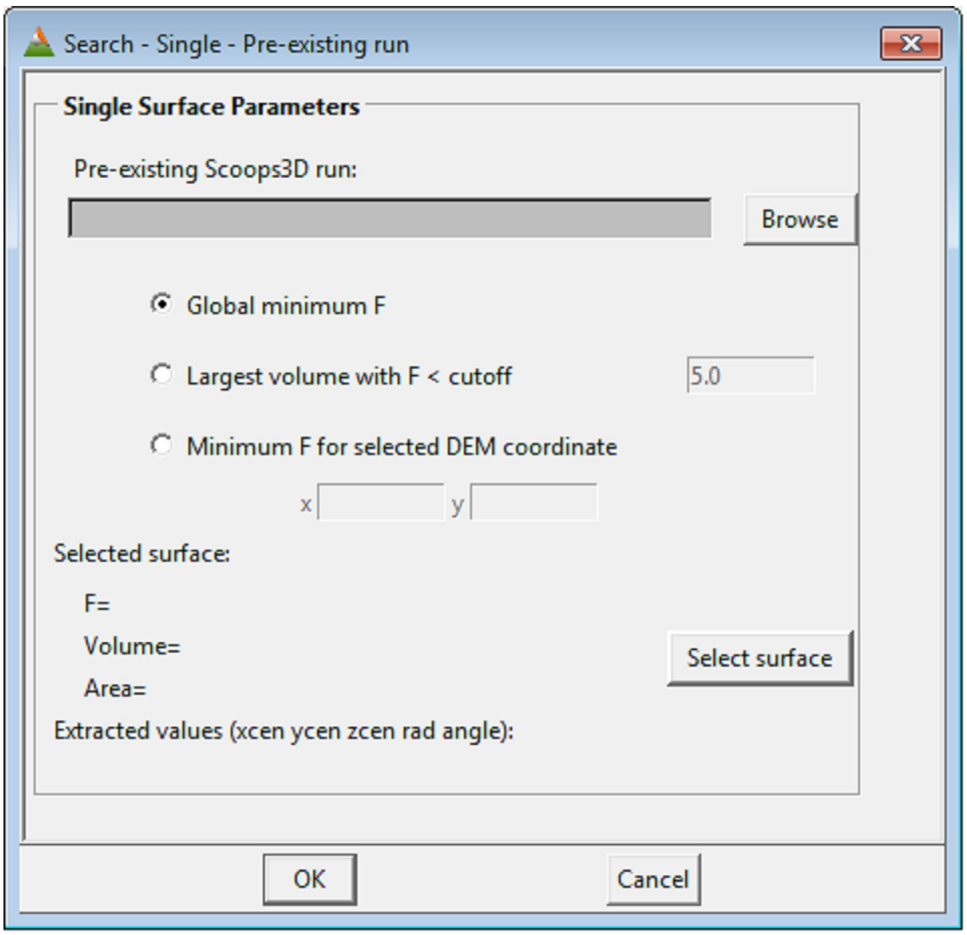


Figure 4.10. Screenshot showing window in Scoops3D-i for selecting a single trial surface from a pre-existing Scoops3D run.

If the **Enter manually** option is selected and **Next** is clicked, then the window shown in figure 4.11 opens. This option allows the user to manually define the rotational center of a trial sphere; no pre-existing output is needed. The center of the sphere is defined by x-, y-, and z- coordinates as well as a radius. **The x-, y-, and z-coordinates are specified in the length units and coordinate system of the DEM, where the coordinates of the lower left corner are defined in the DEM header by xllcorner, yllcorner** (see example in section 4.4.2.1, fig. 4.20). The user can also specify a slip direction in degrees counter-clockwise from the positive x-axis (this parameter, ***angle***, is further explained in section 4.4.1.1.9.2) or check the box to use the overall fall direction (defined relative to the ground surface). In both cases, the slip direction defines the axis of rotation. Click **OK** when finished to return to the main window.

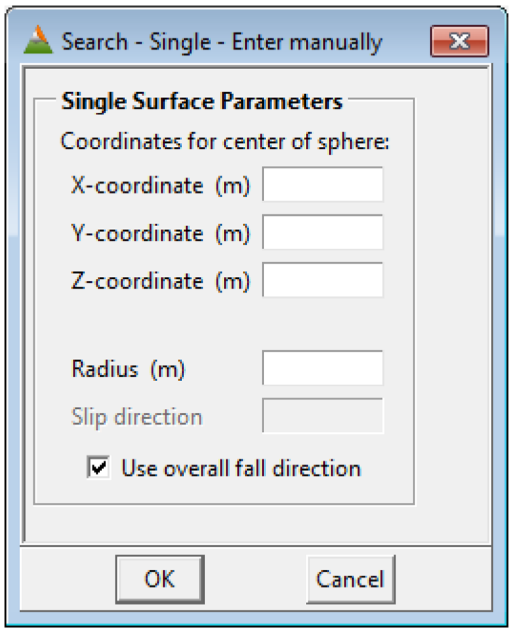


Figure 4.11. Screenshot showing window in Scoops3D-i for manually defining a single trial surface.

4.3.3.5.3. File Search

Selection of the file search method opens the window shown in figure 4.12. This option has similar parameters to the Box Search method (section 4.3.3.5.1), except that the horizontal extent of the initial coarse search is controlled by the contents of a file that can be chosen by clicking the **Browse** button. This file should be in ASCII raster grid format as described in section 4.4.2.1. Limiting the horizontal extent of the search through this option can shorten computational time when the area of interest in the DEM is irregularly shaped. The **Advanced** button functions similarly to that for the Box Search (section 4.3.3.5.1). Click **OK** when finished to return to the main window.

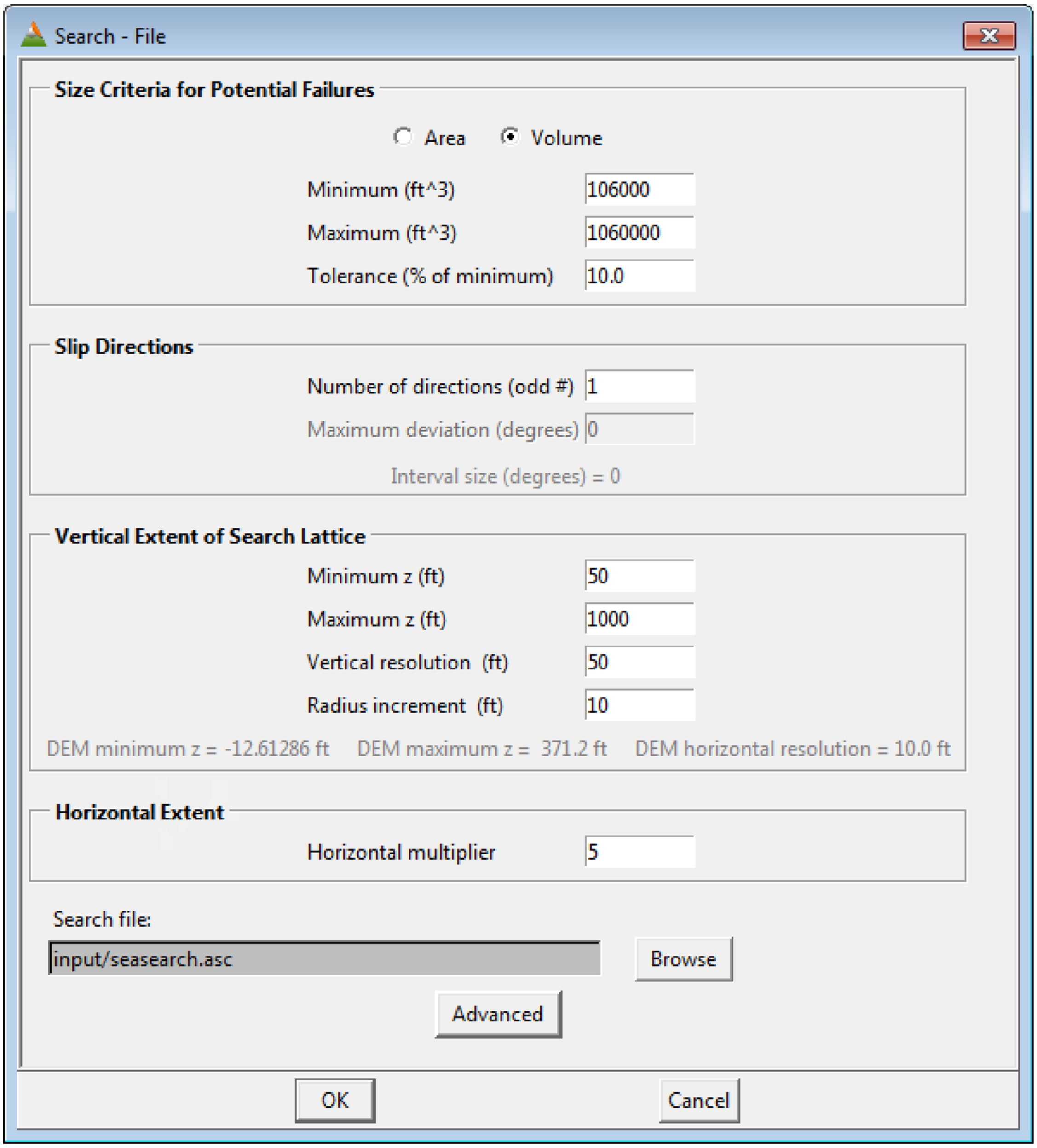


Figure 4.12. Screenshot showing **Search Configuration** window in Scoops3D-i for the "file" search method. Window shown is from Scoops3D Seattle example P (file name: *P_seadry.scp*) described in section 7.5.

4.3.3.6. Additional Output Options

Additional output options can be selected by clicking **Options** > **Output Files** from the main window menu bar. The user does not need to select this option - Scoops3D creates the standard default output files (section 4.5.1) if this option is ignored. If this option is selected, then the **Options – Output Files** window shown in figure 4.13 appears. The user can choose to have Scoops3D create a new DEM file with a user-selected mass or masses removed, based on results from a stability analysis of the original DEM. Options for a new DEM include: removing only the mass with the global minimum factor of safety, *F*, less than a selected cutoff value; removing all masses with *F* less than a cutoff value; or removing only the largest (based on the primary size criterion) mass with *F* less than a cutoff value. The default *F* cutoff value is 10. The initial default setting does not create a new DEM file.

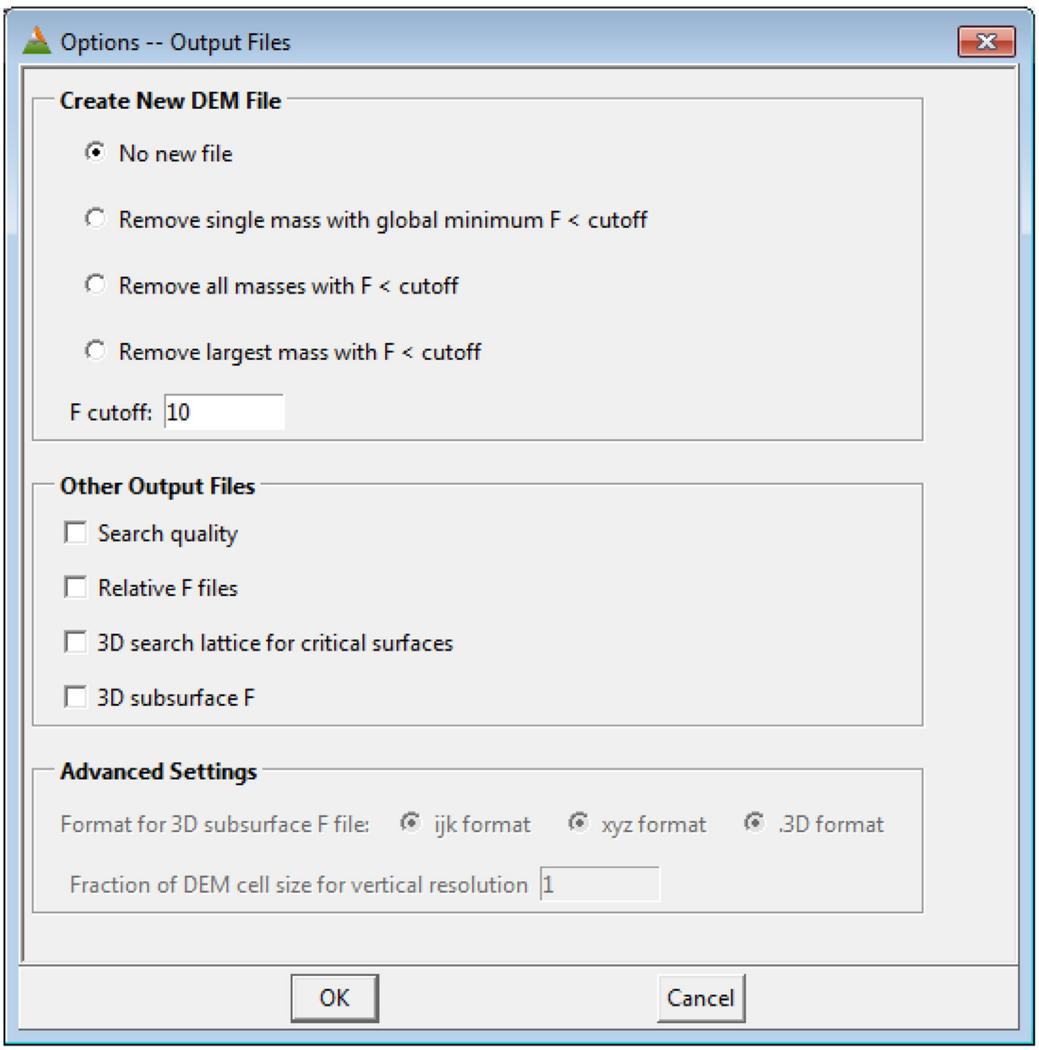


Figure 4.13. Screenshot showing window in Scoops3D-i for selecting optional output files.

Other optional output files include any of the following: search quality files, a relative factor-of-safety file, a 3D search-lattice file, and (or) a 3D subsurface factor-of-safety file. These can be selected by checking the appropriate boxes in the **Options – Output Files** window. More complete descriptions of these output file options are provided in section 4.5.3. Click **OK** when finished to return to the main window.

4.3.3.7. Save a Scoops3D Input File

When finished entering parameters for the primary input file, select **File > Save** (if the file name remains the same). Alternatively, select **File** > **Save As** (if a new name is desired) from the main window menu bar**,** navigate to the appropriate directory (folder), enter a file name to identify the new input file, and click **Save**. The file will be saved with a .scp extension.

4.3.4. View and/or Modify an Existing Scoops3D Input File

An existing Scoops3D input file can be readily viewed and (or) modified using Scoops3D-i. From the main window menu bar, select **File** > **Open**, navigate to the desired directory (folder) containing the existing .scp file, select the file, and click **Open**. If the file has been opened recently, it may be opened by selecting **File > Open Recent** and choosing the desired file name. The main Scoops3D-i window then displays the contents of the existing .scp input file. An errorlog.txt window opens if linked files (such as the DEM or material layer files) are not found in the directories listed in the .scp file. If child windows are opened, such as the **Subsurface Parameters** or **Search Configuration** windows, they also display the relevant information contained in the .scp file. Recall that incomplete "in-progress" .scp files may exist. Thus, some parameters may be absent – these need to be entered before running Scoops3D. The text content of the .scp file can be viewed by selecting **View** > **Scoops3D Input File** from the main window menu bar. Existing .scp files can be readily modified and saved using the procedures described in section 4.3.3.

4.3.5. Create a New Input File for Scoops3D Using a Single Trial Surface from a Previous Scoops3D Run

Scoops3D-i can be used to examine the factor of safety and volume of a selected trial surface obtained from a previous Scoops3D run. The sequence of steps described here allows the user to start with the material properties and groundwater configuration defined in a previous Scoops3D run and modify them as desired. From the main window menu bar, select **File > Open**, navigate to the appropriate directory (folder) containing the existing .scp file, then select the file and click **Open**. Next, select **File > Save As**, navigate to the appropriate directory (folder) file, enter a new file name, and click **Save.** This sequence will preserve the previous run files. Then, in the main Scoops3D-i window, select single surface for the **Search method** and click **Search Configuration**. **Pre-existing run** is selected by default. Click **Next** to proceed to the next window. Click on the **Browse** button to select the pre-existing .scp file from a previous Scoops3D run. Then pick a selection: (1) the single surface with the global minimum *F* for the entire DEM, (2) the single surface having the largest volume with *F* less than some chosen cutoff value, or (3) the single surface having the lowest *F* at a specified location in the DEM. **The x- and y-coordinates for this latter selection are specified in the coordinate system of the DEM where the coordinates of the lower left corner are defined in the DEM header by xllcorner, yllcorner** (see section 4.4.2.1 and fig. 4.20). Click **OK** when finished to return to the main window. Modify other parameters as desired and select **Run > Run Scoops3D** to analyze the selected single trial surface. This procedure can be a useful analysis tool for testing sensitivity on a given trial surface, but keep in mind that the single surface with the global minimum *F* for the initial run may not be the same surface identified if the user conducts a new search with the modified parameters.

4.3.6. Check a Scoops3D Input File for Completeness

Before running Scoops3D, the user can check the main parameter input file for completeness and check for the existence of additional input files such as the DEM or layer files. Scoops3D-i can perform these checks for the currently open .scp input file by selecting **Run > Check Input File** from the main window menu bar. A window displays any missing values and the names of any missing input files. **Note that this option only checks for the existence of the additional input files beyond the main parameter file; it does not determine whether the additional files contain data in the correct file formats.**

4.3.7. Run Scoops3D from Scoops3D-i

Scoops3D can be run directly from the user interface, Scoops3D-i. After opening (by selecting **File > Open**) or creating a complete .scp input file, start Scoops3D by selecting **Run > Run Scoops3D** from the main window menu bar. Before launching Scoops3D, Scoops3D-i checks the input file for completeness, as described in section 4.3.6. If the input file is found to be OK, then Scoops3D is launched. As Scoops3D runs, the initially blank command tool window displays successive lines containing the current input file name, search node, search iteration number (for a coarse-to-fine search), the percentage completed of a specific search iteration, and the number of trial surfaces analyzed so far. If a simple search is selected, this window displays the percentage completed of the entire search and the number of trial surfaces analyzed. This display allows the user to determine how the Scoops3D simulation is progressing. When the run is completed, “Successful execution …” with Scoops3D version number, date, and time are displayed. Output files are placed in the subdirectory (folder) titled <*filein*>*_output* under the directory (folder) containing the .scp input file, where <*filein*> is the prefix to the .scp file.

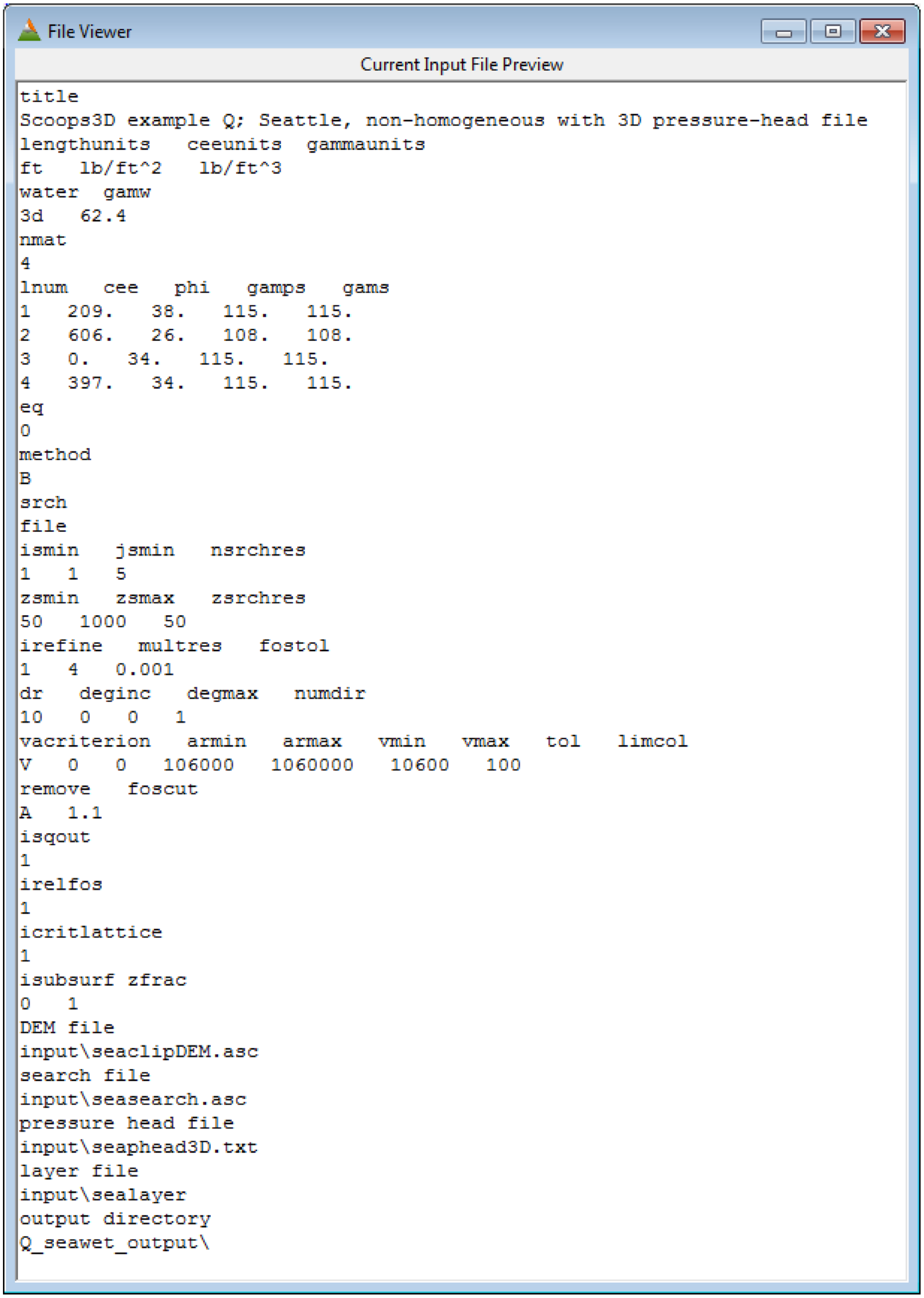
Multiple Scoops3D runs can be performed simultaneously from Scoops3D-i. To perform an additional run while other runs are ongoing, open or create a different .scp input file and select **Run > Run Scoops3D.** Information about the simulation progress for all active runs is displayed in the Scoops3D-i window, but information from multiple simultaneous runs may be mixed in the window. Information for a particular run can be identified by the .scp file name at the beginning of each display line.

4.3.8. Stop a Scoops3D Run in Progress

Occasionally a user may want to stop a Scoops3D simulation run before it is completed. This can be achieved using Scoops3D-i by selecting **Run > Stop Scoops3D** from the main window menu bar and selecting the appropriate .scp file name from the list, provided the run was initiated in the current session of Scoops3D-i. The run then terminates and leaves the various output files incomplete. Other active simulations continue running.

4.3.9. View Text-Based Input and Output Files

The main parameter input file can be viewed using Scoops3D-i. To view this input file, open a .scp file and then select **View > Scoops3D Input File** from the main window menu bar. The file contents are displayed in a separate window; an example is shown in figure 4.14. If the main output file associated with the open .scp file exists, it can be viewed by selecting **View > Scoops3D Output File**. Other text files, including any of the Scoops3D output files, can be viewed by selecting **View > ASCII Text File** and selecting the appropriate file from the navigation window. View windows can be closed by clicking the red close button at the top of the windows.




```
title
Scoops3D example Q; Seattle, non-homogeneous with 3D pressure-head file
lengthunits   ceeunits   gammaunits
ft   lb/ft^2   lb/ft^3
water  gamw
3d   62.4
nmat
4
lnum   cee   phi   gamps   gams
1   209.   38.   115.   115.
2   606.   26.   108.   108.
3   0.   34.   115.   115.
4   397.   34.   115.   115.
eq
0
method
B
srch
file
ismin   jsmin   nsrchres
1   1   5
zsmin   zsmax   zsrchres
50   1000   50
irefine   multres   fostol
1   4   0.001
dr   deginc   degmax   numdir
10   0   0   1
vacriterion   armin   armax   vmin   vmax   tol   limcol
V   0   0   106000   1060000   10600   100
remove   foscut
A   1.1
isqout
1
irelfos
1
icritlattice
1
isubsurf zfrac
0   1
DEM file
input\seaclipDEM.asc
search file
input\seasearch.asc
pressure head file
input\seaphead3D.txt
layer file
input\sealayer
output directory
Q_seawet_output\
```

Figure 4.14. Screenshot showing window in Scoops3D-i displaying an example of the main parameter input file for Scoops3D. This example has four layers with variable material properties and a groundwater configuration defined in a 3D pressure-head file. Taken from Seattle example Q (file name: *Q_seawet.scp*) described in section 7.5.

4.3.10. Delete Scoops3D Output Files

To remove all output files associated with a previous Scoops3D run, first open the appropriate .scp input file in Scoops3D-i. Then select **Run** > **Delete Scoops3D Output** from the main window menu bar. A window lists the files that will be deleted. Clicking **OK** deletes these files (leaving a potentially empty output directory or folder) and returns the user to the main Scoops3D-i window. If desired, the user can then delete the output directory and (or) .scp file using the sequence appropriate for the user's computer operating system outside of Scoops3D-i.

4.3.11. Get Help for Scoops3D-i

Additional help for using Scoops3D-i is available from the **Help** pull-down menu in the main window tool bar. Selecting **Help** > **Scoops3D Manual** brings up a pdf version of the manual. Selecting **Help** > **Scoops3D Variable Descriptions** opens a new window containing a brief list of the input parameters used in Scoops3D-i. Selecting **Help** > **Balloon Help** toggles on information balloons that briefly appear when using the cursor to hover over various parameters in the Scoops3D-i windows. Clicking this option again toggles off balloon help. Selecting **Help** > **About** provides information about Scoops3D-i (such as version number) and a URL where the latest version of the software can be obtained over the Internet from a USGS web site.

4.4. Program Input

This section details the input files and parameters needed to perform a slope-stability analysis in Scoops3D. At least two input files are always required: (1) the DEM file covering the area of interest and (2) the main parameter input file that contains control variables, search criteria, and material properties. Additional files are required for problems with a separate search file, multiple material layers with differing properties, 3D material properties, a piezometric surface, or 3D pore-pressure head data (table 4.1). Scoops3D-i can be used to build the main parameter input file and to select the additional files (section 4.3.3). When run at the command-line, Scoops3D prompts the user for the main parameter input file name at the beginning of the run – this main file lists all the additional files. The complete file pathname for each input file may include as many as 220 characters.

Table 4.1. Descriptions of Scoops3D input files including recommended file extensions.

[Input files contain three possible types of data: (1) text – a text listing of input parameters (section 4.4.1), (2) grid – raster grid data in Esri ASCII format (section 4.4.2.1), or (3) 3D – listing of 3D coordinates and pressure head or material properties at the specified coordinate that must include mandatory Scoops3D header information (section 4.4.2.2). Grid files may contain user-specified null values (equivalent to NODATA_values) as specified in the file header]

Section	File description[1]	Criteria for optional files	File extension	Data type	Description
Required files					
4.4.1	Main parameter input file	---	.scp	Text	Material and search parameters, and input file names
4.4.2.1.2	DEM	---	.asc	Grid	Digital elevation model
Optional files[2]					
4.4.2.1.3	Restricted search	***srch*** = 'file' or 'FILE'	.asc	Grid	Horizontal location of initial search extent
4.4.2.1.4	Material layers	***nmat*** > 1	.asc	Grid	Elevation of bottom of material layers, n-1 number of files are needed to match n number of layers
4.4.2.1.5	Piezometric surface	***water*** = 'pz' or 'PZ'	.asc	Grid	Elevation of groundwater table
4.4.2.2.4	3D pressure head	***water*** = '3d' or '3D'	.txt or other	3D[3]	3D distribution of pressure head
4.4.2.2.4	3D variably saturated pressure head and water content	***water*** = 'vs' or 'VS'	.txt or other	3D[3]	3D distribution of variably saturated pressure head and water content
4.4.2.2.5	3D variably saturated pressure head	***water*** = 'vg', 'VG', 'fx' or 'FX'	.txt or other	3D[3]	3D distribution of variably saturated pressure head
4.4.2.2.6	3D material properties	***str3d*** = 1	.txt or other	3D[3]	3D distribution of material properties, such as strength and (or) unit weights

[1]File names are user-defined.

[2]Required if specific options are selected in the main parameter input file.

[3]3D files have various formats—see section 4.4.2.2.

The file format and data contents for each input file are described in the following sections. Files required for all problems are designated with a REQUIRED label.

4.4.1. Main Parameter Input File

REQUIRED.

FORMAT: text. Scoops3D-i, designates these files with a .scp extension.

This required input file contains information about subsurface material properties (shear strengths, unit weights, groundwater conditions, earthquake loading coefficient), the slope-stability analysis method, the search-lattice configuration, and output file options. The last lines of this file contain operating system-specific pathnames to the DEM file and any additional input files.

The main parameter input file is most easily created using Scoops3D-i (see section 4.3). Scoops3D-i helps the user create an internally consistent and complete parameter input file. The parameter input file can also be created or modified from an existing input file using a text editor. **Note that there must be a carriage return after the last data value in this file for the input to be read completely.**

Input parameters in this file must be entered as a series of ***parameter-line pairs***; these two-line pairings are demonstrated in the example input files shown in figures 4.15 and 4.16. The first line of each pair is descriptive and the first word in the line is the ***parameter-line id***; the second line contains the actual numeric or alphanumeric values. Scoops3D-i creates parameter input files with labels for all of the parameters in each line pair. Parameter values are read in free form and do not require a specific format or specific spacing between entries. Any parameter-line pairs that do not start with the first two letters of a recognized parameter-line id label are ignored. Blank lines between two-line pairs are also ignored; however, no lines can separate the first and second lines of a specific parameter-line pair**. If comment lines are desired, we recommend starting those lines with non-alphanumeric values (for example, !!! or #) to avoid any chance of confusion by accidental replication of a valid parameter-line id.**

Most of the parameter-line pairs can be placed in any order within the main parameter input file. However, some crucial parameter pairs require specific ordering, and these are noted in their individual descriptions below. Scoops3D-i automatically provides valid line ordering.

```
title                                             # section 4.4.1.1.1
Scoops3D example R; Mount Saint Helens
lengthunits  ceeunits gamrunits                   # section 4.4.1.1.2
m  kPa  kN/m^3
water                                             # section 4.4.1.1.3
no
nmat                                              # section 4.4.1.1.4.1
1
lnum  cee  phi  gamt                              # section 4.4.1.1.4.1
1  1000.  40.  24.
eq                                                # section 4.4.1.1.5
0
method                                            # section 4.4.1.1.6
B
srch                                              # section 4.4.1.1.9
box
ismin  jsmin  ismax  jsmax  nsrchres              # section 4.4.1.1.9.1
1  1  96  91  1
zsmin  zsmax  zsrchres                            # section 4.4.1.1.9.1
1000  9200  100
irefine  multres  fostol                          # section 4.4.1.1.9.1
1  8  0.01
dr  deginc  degmax  numdir                        # section 4.4.1.1.9.1
50  0  0  1
vacriterion  armin  armax  vmin  vmax  tol  limcol     # section 4.4.1.1.10
V  0  0  .10E+9  3.5E+9  10000000.0  100
remove  foscut                                    # section 4.4.1.1.11.1
M  5.0
isqout                                            # section 4.4.1.1.11.2
1
irelfos                                           # section 4.4.1.1.11.3
1
icritlattice                                      # section 4.4.1.1.11.4
1
ilattice                                          # section 4.4.1.1.11.5
1
isubsurf zfrac                                    # section 4.4.1.1.11.6
1  1
DEM file                                          # section 4.4.1.1.12
input\sthel_res100mDEM.asc
output directory                                  # section 4.4.1.1.13
R_sthel_output\
```

Figure 4.15. Text listing showing an example of a Scoops3D main parameter input file configured for homogeneous material with a box search and optional output files. Parameter-line pairs are distinguished by a line ID containing text descriptors followed by a line containing the parameter values. These lines are keyed by section numbers (for example, 4.4.1.1.1) for reference purposes; each section contains a complete description of the line pair. Note that files created by Scoops3D-i list full path names for input and output files, but the Scoops3D example files, including the one shown here, use relative path names (see chapter 7). Example is taken from Mount St. Helens example R (file name: *R_sthel.scp*) described in section 7.6.

```
title                                                                                                   # section 4.4.1.1.1
Arai and Tagyo 1985, 3D material properties combined w/ 3D pressure head file
lengthunits  ceeunits gamrunits                                                                         # section 4.4.1.1.2
m  kPa  kN/m^3
water gamw                                                                                              # section 4.4.1.1.3
3d  9.81
str3d  linterp                                                                                          # section 4.4.1.1.4.2
1  0
nmat                                                                                                    # section 4.4.1.1.4.1
1
lnum  cee  phi  gamps  gams                                                                             # section 4.4.1.1.4.1
1  -1  -1  -1  -1
eq                                                                                                      # section 4.4.1.1.5
0
method                                                                                                  # section 4.4.1.1.6
B
srch                                                                                                    # section 4.4.1.1.9
single
xcen  ycen  zcen  rad  angle                                                                            # section 4.4.1.1.9.2
25.25  33.25  47  33.76  365
remove  foscut                                                                                          # section 4.4.1.1.11.1
M  10
isqout                                                                                                  # section 4.4.1.1.11.2
0
irelfos                                                                                                 # section 4.4.1.1.11.3
0
icritlattice                                                                                            # section 4.4.1.1.11.4
0
isubsurf zfrac                                                                                          # section 4.4.1.1.11.6
0  1
DEM file                                                                                                # section 4.4.1.1.12
C:\Users\SCOOPSuser\Scoops3D\examples\AraiTagyo\input\emb20dem.asc
pressure head file                                                                                      # section 4.4.1.1.12
C:\Users\SCOOPSuser\Scoops3D\examples\AraiTagyo\input\emb20phead3D.txt
material properties file                                                                                # section 4.4.1.1.12
C:\Users\SCOOPSuser\Scoops3D\examples\AraiTagyo\input\emb20mat3d.txt
output directory                                                                                        # section 4.4.1.1.13
C:\Users\SCOOPSuser\Scoops3D\examples\AraiTagyo\emb20_single_output\
```

Figure 4.16. Text listing of an example of a Scoops3D main parameter input file configured for a single trial surface computation (***srch*** = ‘single’) with a 3D material property file and a 3D pore-pressure file. Parameter-line pairs are distinguished by a line ID containing text descriptors followed by a line containing the parameter values. These lines are keyed by section numbers (for example, 4.4.1.1.1) for reference purposes.

4.4.1.1. Input Parameter Descriptions

This section describes each set of parameters. The parameter-line id label (LINE ID) is shown for each line pair, followed by the name and description of each parameter contained in the second line of the pair. Any limits on the parameters, their variable type (character, numeric, integer), and naming conventions are described in these sections.

4.4.1.1.1. Title

NOT REQUIRED by Scoops3D, but required in Scoops3D-i.

LINE ID: `title`

title user-defined description line, maximum of 120 characters. (Character).

4.4.1.1.2. Unit Descriptors

NOT REQUIRED.

Note that unit names are for descriptive purposes only; **Scoops3D does not check whether the units are internally consistent nor does it convert any units to be consistent with the others**.

LINE ID: `lengthunits ceeunits gamrunits`

lengthunits user-defined units of length (for example, ‘m’ or ‘ft’). Note that all input parameters and data contained in other input files should use consistent units (for example, DEM, layer and piezometric surface elevations, and 3D pressure-head values should be in the same length units). (Character, maximum length of two characters).

ceeunits user-defined units for cohesion (for example, ‘kPa’ or ‘lb/ft^2’). (Character, maximum length of eight characters).

gamrunits user-defined units for unit or specific weights (for example, ‘kN/m^3’ or ‘lb/ft^3’). (Character, maximum length of eight characters).

4.4.1.1.3. Groundwater Options

NOT REQUIRED.

If this pair is absent, then no groundwater pore pressures are used in the stability computations. Note that this line pair must come before the material properties line pair (section 4.4.1.1.4). Section 2.4 describes how different groundwater options are used in the computation of factor of safety. The options with 3D variably saturated or unsaturated pressure heads (‘vs’,’vg’, or ‘fx’) cannot be used with a 3D material properties file.

LINE ID: `water gamw`

water two character descriptor that indicates which method is used to determine pore-water pressures for the slope-stability computations. Seven options are available. If ***water*** = ‘no’ or ‘NO’, no pore pressures are used in calculations. If ***water*** = ‘ru’ or ‘RU’, a fraction of overlying column weight is used as an approximation of pore pressure and this pore-pressure ratio must be specified for each material layer in the property layers input. If ***water*** = ‘pz’ or ‘PZ’ (piezometric or water table surface), ‘3d’ or ‘3D’ (3D pressure heads), ‘vs’ or ‘VS’ (3D variably saturated pressure heads and water contents), ‘vg’ or ‘VG’ (van Genuchten SWCC and 3D variably saturated pressure heads), or ‘fx’ or ‘FX’ (Fredlund and Xing SWCC and 3D variably saturated pressure heads), the corresponding file name must be included at the end of the parameter input file. The formats and pathname requirements for these files are described below. (Character, ‘no’, ‘NO’, ‘ru’, ‘RU’, ‘pz’, ‘PZ’, ‘3d’,‘3D’, ‘vs’, ‘VS’,’vg’,’VG’,’fx’, or ‘FX’).

gamw unit weight of water (γ_w) in units consistent with all other parameters. Only required if ***water*** = ‘pz’ (or ‘PZ’), ***water*** = ‘3d’ (or ‘3D’), ***water*** = ‘vs’ (or ‘VS’), ***water*** = ‘vg’ (or ‘VG’), or ***water*** = ‘fx’ (or ‘FX’). (Numeric, ≥ 0).

4.4.1.1.4. Material Properties

REQUIRED.

One of the following options is required (see sections 4.4.1.1.4.1 or 4.4.1.1.4.2). The user may select either an option for material layers (using ***nmat*** and associated ***lnum*** lines) or an option for using a 3D distribution contained in a separate file. If a homogeneous or uniform domain is desired, the user should use the option described in section 4.4.1.1.4.1 with one layer (***nmat*** = 1). If only some of the material properties are contained in a 3D file, the other properties should be designated using the homogeneous, one-layer method.

4.4.1.1.4.1. Property Layers Option

This option requires the ***nmat*** line pair and associated ***lnum*** line pairs describing the material properties for each layer. For example, if the user specifies three layers (***nmat*** = 3), there must also be three pairs of ***lnum*** lines to designate the properties for each layer. Separate input files define the bottom elevation for each material layer (section 4.4.2.1.4). **Note that all material parameters should have consistent units with each other and with the units of the DEM.**

LINE ID: `nmat`

nmat the number of layers used to define material properties for the slope-stability computations. (Integer, ≥ 0).

The parameters contained in the ***lnum*** line pairs depend on the groundwater option selected, as follows:

If no groundwater (***water*** = 'no' or 'NO') then:

LINE ID: `lnum cee phi gamt`

or, if pore-pressure ratio (***water*** = 'ru' or 'RU') then:

LINE ID: `lnum cee phi gamt ru`

or, if piezometric surface (***water*** = 'pz' or 'PZ') or if 3D pressure-head file (***water*** = '3d' or '3D') then:

LINE ID: `lnum cee phi gamps gams`

or, if 3D variably saturated pressure-head and water content file (***water*** = 'vs' or 'VS') then:

LINE ID: `lnum cee phi gams thetares thetasat`

or, if van Genuchten SWCC and 3D variably saturated pressure-head file (***water*** = 'vg' or 'VG') then:

LINE ID: `lnum cee phi gams thetares thetasat vgalpha vgn`

or, if Fredlund and Xing SWCC and 3D variably saturated pressure-head file (***water*** = 'fx' or 'FX') then:

LINE ID: `lnum cee phi gams thetares thetasat fxa fxn fxm fxr`

where:

lnum the layer identification number. (Integer, > 0 and ≤ nmat).

cee cohesion (c) for a layer. (Numeric, ≥ 0).

phi angle of internal friction (ϕ) for a layer, in degrees. (Numeric, ≥ 0).

gamt total unit weight (γ_t) for a layer of earth material. This value is required if either the no pore pressure option (***water*** = 'no' or 'NO') or the pore-pressure ratio option (***water*** = 'ru' or 'RU') is selected. (Numeric, ≥ 0)

gamps partially saturated unit weight (γ_{ps}) for a layer of earth material, used for materials above the piezometric or zero-pressure surface. This value is required if either the piezometric surface option (***water*** = 'pz' or 'PZ') or 3D pressure-head file option (***water*** = '3d' or '3D') is selected. It is NOT used for variably saturated configurations (***water*** = 'vs', 'VS', 'vg', 'VG', 'fx', 'FX'). (Numeric, ≥ 0).

gams saturated unit weight (γ_s) for a layer of earth material, used for materials below the piezometric surface or where positive pore pressures are specified by a 3D pressure-head file. This value is required if either the piezometeric surface option (***water*** = 'pz' or 'PZ'), the 3D pressure-head file option (***water*** = '3d' or '3D'), the 3D variably saturated pressure head and water content file option (***water*** = 'vs' or 'VS'), the van Genuchten SWCC and 3D variably saturated pressure-head file option ('vg' or 'VG'), or the Fredlund and Xing SWCC and 3D variably saturated pressure-head file option ('fx' or 'FX') is selected. (Numeric, ≥ 0).

ru pore-pressure ratio (only required if ***water*** = 'ru' or 'RU'), defined as the ratio of pore pressure to vertical stress, or $r_u = u / \int \gamma_t z dz$ (section 2.4), where u is pore pressure on the trial surface, γ_t is total unit weight (earth material plus pore water), and z is the vertical distance from the trial surface to the ground surface. The value of r_u is used to compute the pore pressure acting on the trial surface of each column within the potential failure mass. The user can specify different r_u values for different layers, but r_u is constant within a layer. Typically, values of r_u are less than 0.5. (Numeric, ≥ 0).

thetares residual water content (θ_r) in partially saturated earth material layer. This value is required if any of the 3D variably saturated options (***water*** = 'vs', 'VS', 'vg', 'VG', 'fx' or 'FX') are selected. (Numeric, ≥ 0).

thetasat saturated water content (θ_s) for a layer of earth material. This value is required if any of the 3D variably saturated options (***water*** = 'vs', 'VS', 'vg', 'VG', 'fx' or 'FX') are selected. (Numeric, ≥ 0).

vgalpha α_{vG} parameter for the van Gunuchten (1980) soil-water characteristic curve (see section 2.4 and equation 2.39). This value is required if the van Genuchten SWCC and 3D variably saturated pressure-head file option (***water*** = 'vg' or 'VG') is selected. (Numeric, > 0).

vgn n_{vG} parameter for the van Gunuchten (1980) soil-water characteristic curve (see section 2.4 and equation 2.39). This value is required if the van Genuchten SWCC and 3D variably saturated pressure-head file option (***water*** = 'vg' or 'VG') is selected. (Numeric, > 0).

fxa a_{FX} parameter for the Fredlund and Xing (1994) soil-water characteristic curve (see section 2.4 and equation 2.40). This value is required if the Fredlund and Xing SWCC and 3D variably saturated pressure-head file option (***water*** = 'fx' or 'FX') is selected. (Numeric, > 0).

fxn n_{FX} parameter for the Fredlund and Xing (1994) soil-water characteristic curve (see section 2.4 and equation 2.40). This value is required if the Fredlund and Xing SWCC and 3D variably saturated pressure-head file option (***water*** = 'fx' or 'FX') is selected. (Numeric, > 0).

fxm m_{FX} parameter for the Fredlund and Xing (1994) soil-water characteristic curve (see section 2.4 and equation 2.40). This value is required if the Fredlund and Xing SWCC and 3D variably saturated pressure-head file option (***water*** = 'fx' or 'FX') is selected. (Numeric, > 0).

fxr ψ_r, residual suction parameter for the Fredlund and Xing (1994) soil-water characteristic curve (see section 2.4 and equation 2.41). This value is required if the Fredlund and Xing SWCC and 3D variably saturated pressure-head file option (***water*** = 'fx' or 'FX') is selected. (Numeric, > 0).

4.4.1.1.4.2. 3D Property File Option

LINE ID: `str3d linterp`

str3d flag indicating that a 3D file is used to specify material properties for the slope-stability computations. If ***str3d*** = 1, the 3D material properties file name must be included at the end of the main parameter input file (fig. 4.16). The format for this file is described in section 4.4.2.2. Note that when using a 3D material properties file, if all properties needed for the simulation are included in the 3D file, the main input file does not need a ***nmat*** line pair. If ***water*** = 'ru' (or 'RU') is specified, then the value for r_u must be constant throughout the domain. If the 3D file contains some but not all of the material properties or ***water*** = 'ru' (or 'RU'), the ***nmat*** and ***lnum*** line pairs (section 4.4.1.1.4.1) must be included with ***nmat*** = 1. Each parameter included in the 3D file must be assigned a value of -1 in the ***lnum*** line. Parameters not in the 3D file are assumed to be constant throughout the domain and set to the value specified in the ***lnum*** line. In the example shown in figure 4.16, ***cee***, ***phi***, and the unit weight values are assigned values of -1 to indicate that they are contained in the 3D material properties file. Note that Scoops3D cannot incorporate 3D distributions of residual, ***thetares***, and saturated, ***thetasat***, water contents in the 3D material properties file. (Integer, 0 or 1).

linterp flag for linear interpolation. If ***linterp*** = 1, Scoops3D linearly interpolates between vertical 3D property data to determine values at the trial surface. Otherwise, Scoops3D uses the values associated with the 3D block containing the trial surface. (Integer, 0 or 1).

4.4.1.1.5. Earthquake Loading

NOT REQUIRED.

LINE ID: `eq`

eq earthquake or seismic loading, imposed as a horizontal pseudo-acceleration coefficient (k_{eq}) and given as a dimensionless coefficient relative to a fraction of gravitational acceleration, g (section 2.3). (Numeric, ≥ 0).

4.4.1.1.6. Slope-Stability Analysis Options

REQUIRED.

LINE ID: `method`

method the limit-equilibrium method used for computing factor of safety. Specify ***method*** = ‘B’ (or ‘b’) to implement Bishop's simplified method or ***method*** = ‘O’ (or ‘o’) for the Ordinary (Fellenius) method. See section 2.3 for a discussion of these methods. If ***method*** = ‘B’ (or ‘b’) is specified, Scoops3D also calculates the factor of safety using the Ordinary method for the critical surfaces identified with Bishop’s method. Note that the critical surfaces found using the two methods may be different. (Character, ‘b’, ‘B’, ‘o’, or ‘O’).

4.4.1.1.7. Iteration Tolerance for Bishop’s Simplified Method

NOT REQUIRED. Only used when ***method*** = ‘B’ (or ‘b’).

This option allows the user to modify the Scoops3D default iteration tolerance (0.0001) used with Bishop’s simplified method (see section 2.3.2). This advanced option is not available in Scoops3D-i. Typically, the user will not need to modify this value. If the default tolerance is adequate, this parameter does not need to be specified.

LINE ID: `diter`

diter a user-defined tolerance level for halting the iteration process when using Bishop's simplified method. If not specified, Scoops3D uses a default value of ***diter*** = 0.0001. Stability computation for a given trial surface is halted when the difference between the factor of safety computed in the current iteration and the previous iteration is less than diter (that is, $|(F_{new}-F_{old})| <$ ***diter***). Trial surfaces that do not reach this tolerance are eliminated from consideration, but they are listed in the files *<filein>_filter_out.txt* and *<filein>_filtergrid_out.asc* (see section 4.5.2). Iterations for trial surfaces that do not reach this tolerance within 10 iterations are terminated unless the solution is converging monotonically. Scoops3D will allow solutions with monotonic convergence to continue up to a maximum of 25 iterations before termination of iteration calculations. See section 2.3.2 for an explanation of the iteration process. The parameter ***diter*** is optional and is only used if ***method*** = ‘B’ or ‘b’. (Numeric, > 0).

4.4.1.1.8. Filter Option for Bishop's Simplified Method

NOT REQUIRED. Only used when ***method*** = 'B' (or 'b').

This option allows the user to filter spurious or unreliable solutions from the search by removing solutions with low values of m_α determined during the iteration process**.** Bishop's simplified method may occasionally converge to an incorrect (very low or negative) value of factor of safety – see section 2.3.2 for more explanation. The effectiveness of filtering can vary between problems; some trial and error investigation may be required to select an appropriate filter value (section 5.3.7).

LINE ID: `absminma`

absminma minimum value of m_α (section 2.3.2) used to filter results when using Bishop's simplified method. If a trial surface has one or more columns with $|m_\alpha|$ < ***absminma***, the surface is eliminated from consideration, but information about the surface is included in *<filein>_filter_out.txt* and *<filein>_filtergrid_out.asc* (see section 4.5.2). The value of m_α depends on a number of factors, including the maximum and minimum dips of columns in the trial surface; the optimal filter value may vary between problems and selecting an appropriate value may require some investigation. If ***method*** = 'O' (or 'o'), this parameter is ignored. (Numeric, > 0).

4.4.1.1.9. 3D Search Options

REQUIRED.

The ***srch*** parameter-line pair is required and subsequent lines depend on the option selected for ***srch***. Three options are available: 'box', 'file', or 'single' and only one can be selected. With box and file options, the user defines the extent of the search lattice. The single option defines one individual trial surface; this option does not invoke a 3D search.

LINE ID: `srch`

srch descriptor that specifies the search option. The required parameters for each option, 'box', 'file', or 'single', are described below (sections 4.4.1.1.9.1, 4.4.1.1.9.2, or 4.4.1.1.9.3, respectively). (Character, 'box', 'BOX', 'file', 'FILE', 'single', or 'SINGLE').

4.4.1.1.9.1. Box Search

If ***srch*** = ‘box’ (or ‘BOX’) then the horizontal extent of the search lattice is a rectangular box defined relative to the DEM. Three parameter-line pairs must be included with this option; an additional line pair for a coarse-to-fine search is optional. Note that the horizontal extent and nodal spacing of the search lattice is specified differently than the vertical extent and spacing.

LINE ID: `ismin jsmin ismax jsmax nsrchres`

ismin, jsmin, ismax, jsmax the horizontal limits of the search lattice relative to the DEM array bounds, expressed as ij cell counters. The lower left cell of the DEM has values i =1, j = 1, where i increases in the positive x direction and j increases in the positive y direction (fig. 4.17). For example, if the search lattice covers the same horizontal extent as the DEM, then ***ismin*** =1, ***jsmin*** = 1, ***ismax*** = ncols, and ***jsmax*** = nrows, where ncols and nrows are the maximum array bounds of the DEM (fig. 4.17*A*). The user can readily select this option when using Scoops3D-i. (Integer).

In some cases, the user may want the search lattice to extend beyond or be restricted to only part of the DEM extent (see sections 3.2 and 5.3.5). For example, if the search lattice needs to extend horizontally beyond the lower and (or) left side boundaries of the DEM grid, then ***ismin*** and (or) ***jsmin*** should be set to an integer value less than 1 (for example, a value of ***ismin*** = 0 starts the search lattice a distance, in the x direction, of one DEM cell spacing away from the center of the leftmost DEM cell, and a value of ***ismin*** = -1 starts the search lattice two cells outside the DEM). Note that search-lattice nodes are located above the centers of the DEM grid cells. For search-lattice coverage beyond the right or upper side of the DEM grid, ***ismax*** and (or) ***jsmax*** should be greater than the maximum array boundaries (fig. 4.17*B*). Likewise, for search-lattice coverage smaller than the DEM grid, use values for ***ismin*** and ***jsmin*** greater than one and values for ***ismax*** and ***jsmax*** less than the DEM boundaries (fig. 4.17*C*). In all cases with this option, the horizontal extent of the search lattice forms a rectangle. (Integers).

nsrchres a multiplier used to control the horizontal (x and y) nodal spacing of the search lattice relative to the resolution of the DEM grid. If ***nsrchres*** = 1, the search-lattice spacing in the horizontal directions equals the DEM grid resolution. The horizontal search grid spacing cannot be finer than the DEM grid resolution (***nsrchres*** $\geq$ 1). If a coarse-to-fine search is selected, ***nsrchres*** is the spacing of the finest search lattice (see also the ***irefine*** line pair discussed below). (Integer, > 0).

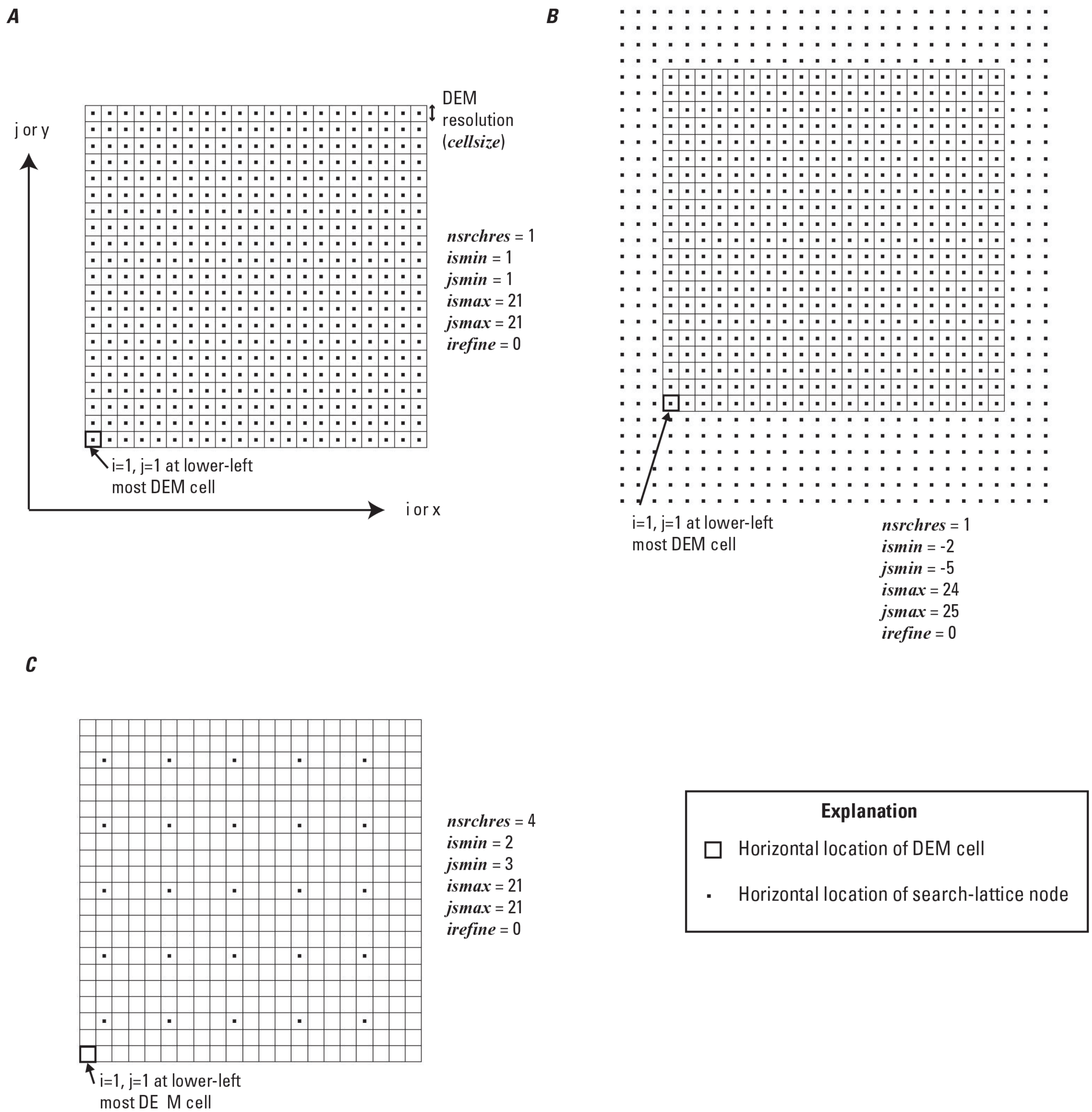


Figure 4.17. Multiple diagrams illustrating different parameter configurations controlling the horizontal spacing of the search lattice. Each diagram shows a plan view of a DEM grid (squares) and search lattice (nodal points centered above the DEM cells). Note that for illustrative purposes, the DEM shown has only 21 rows and columns; it likely would not provide a sufficient number of columns for a good estimate of factor of safety. *A*, Search-lattice spacing matches the horizontal extent and spacing of the DEM grid. *B*, Search lattice extends beyond the DEM grid with a spacing that matches the DEM cell size (***nsrchres*** = 1). *C*, Search-lattice horizontal extent is less than the DEM boundaries and lattice node spacing is larger than the DEM cell size (***nsrchres*** = 4).

LINE ID: `zsmin zsmax zsrchres`

zsmin the minimum elevation of the search-lattice nodes, in the same length units as the DEM (fig. 4.18). If ***zsmin*** is located below the surface of the DEM at a specific horizontal search-lattice location, Scoops3D calculates the elevation of the first search-lattice node as ***zsmin*** plus a multiple of ***zsrchres***, so that the lattice node being used is always above the DEM. (Numeric).

zsmax the maximum elevation of the search lattice, in the same length units as the DEM. (Numeric).

zsrchres the vertical (z) spacing between search-lattice nodes in the same length units as the DEM. The value of ***zsrchres*** may be any number and need not be a multiple of the DEM grid resolution (unlike ***nsrchres***). (Numeric, > 0).

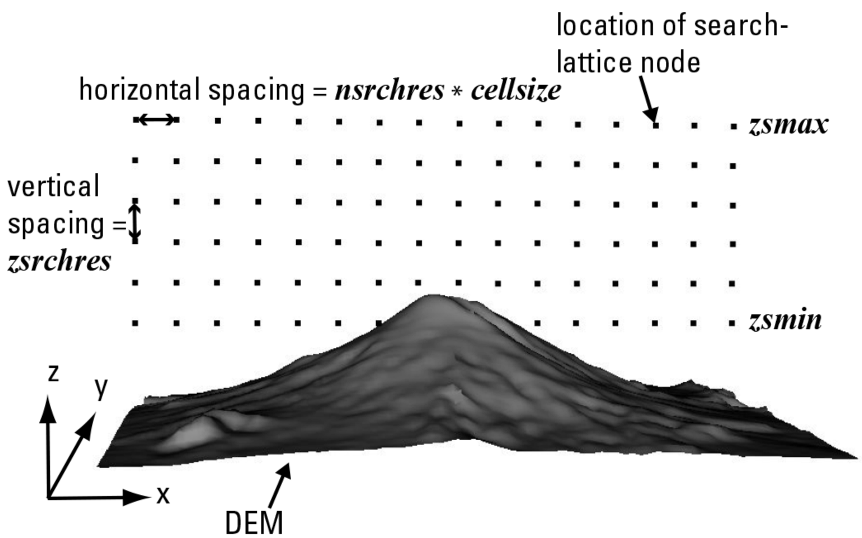


Figure 4.18. Diagram illustrating the parameters controlling the horizontal and vertical search node spacing as well as the vertical limits (***zsmin*** and ***zsmax***) of the search lattice. A perspective view of a DEM and one vertical slice through a 3D search lattice is shown. Note that the parameter describing horizontal spacing (***nsrchres***) is a multiplier of the DEM cell size, whereas the parameter describing the vertical spacing (***zsrchres***) is in length units of the DEM and need not be a multiple of the DEM cell size.

LINE ID: `dr deginc degmax numdir`

dr the radius increment used to construct trial surfaces, in the same length units as the DEM. The value of ***dr*** is used to systematically increase the radius of the spheres generated around each search-lattice node. This systematic increase creates a series of trial surfaces ranging in size between the user-specified minimum and maximum volumes or areas (section 4.4.1.1.10). Scoops3D determines an initial radius for each node that creates a trial failure with a size (volume or area) near the user-specified minimum (within a user-specified tolerance) for the primary size criterion. Subsequent trial surfaces at the same search-lattice node are obtained by increasing the sphere radius by ***dr***, until the potential failure mass exceeds the user-specified maximum volume or area or it intersects a DEM boundary. (Numeric, > 0).

deginc the degree increment for analyzing additional slip directions (for a given trial surface) located to either side of the overall fall direction (fig. 4.19). The azimuthal overall fall direction is found from the average ground-surface slope direction for all full DEM cells contained in the potential failure mass (see section 2.2); Scoops3D always computes the factor of safety for potential slip in this direction. To analyze only trial surfaces rotating in the direction of the overall fall direction, the user should set ***deginc*** = 0. In some cases, such as those with a very uneven distribution of mass or strength, the minimum factor of safety for a given trial surface may be in a direction that differs from the overall fall direction. To analyze potential slip in other directions, the user needs to input values for both ***deginc*** and ***degmax***. (Numeric, ≥ 0).

degmax the maximum deviation, in degrees, to analyze slip directions on either side of the overall fall direction (fig. 4.19). Note that ***degmax*** must be a multiple of ***deginc***. If ***degmax*** is smaller than ***deginc***, Scoops3D sets ***degmax*** to 0 and only analyzes the overall fall direction. (Numeric, ≥ 0).

numdir number of slip directions analyzed for each potential failure mass, including the overall fall direction ((2****degmax***)/***deginc*** + 1). This parameter is used by Scoops3D-i and is ignored by Scoops3D. (Integer, odd value ≥ 1).

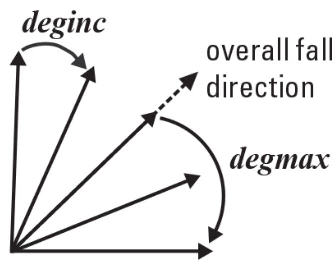


Figure 4.19. Diagram illustrating parameters used to analyze slip directions that differ from the azimuthal overall fall direction.

LINE ID: `irefine multres fostol`

This line pair is optional.

irefine flag to specify the coarse-to-fine search method where an initial coarse search is performed with subsequent search refinement (see section 3.2.2 for details of this method). If ***irefine*** = 1, this option is implemented and both ***multres*** and ***fostol*** must be defined. If ***irefine*** = 0, ***multres*** and ***fostol*** are ignored. (Integer, 0 or 1).

multres multiplier to define the spacing of the initial coarse search lattice. The initial coarse search node spacing in a horizontal plane is ***multres****nsrchres****DEM cell size and the node spacing in a vertical plane is defined by ***multres****zsrchres***. The finest search node spacing is defined by ***nsrchres****DEM cell size (horizontally) and ***zsrchres*** (vertically). (Integer, > 0).

fostol tolerance in computed factor of safety used to halt fine search iterations, expressed in percent. When the percentage difference in computed factor of safety for all DEM cells in the current iteration compared to those from previous iteration (defined as $((F_{new} - F_{old}) / F_{old}) * 100$) is less than ***fostol***, then the search is finished. (Numeric, %, > 0).

4.4.1.1.9.2. Single Trial Surface

If ***srch*** = 'single' (or 'SINGLE') then Scoops3D calculates the stability of a single user-defined trial surface. Only the following parameter-line pair is needed for this option. Commonly, these values are obtained from a previous Scoops3D run.

LINE ID: `xcen ycen zcen rad angle`

xcen, ycen, zcen coordinates of the center for the single trial surface, specified in the coordinate system of the DEM. If these values are obtained from a previous Scoops3D analysis, then they represent the coordinates of one of the search-lattice nodes. (Numeric).

rad length of the radius (expressed in length units of the DEM) of the spherical surface containing the single trial surface. (Numeric, > 0).

angle azimuthal slip direction of the single trial surface in degrees counter-clockwise from the positive x-axis. If the slip direction is unknown, the user can specify a value of ***angle*** > 360º (for example, see fig. 4.16) and Scoops3D calculates and uses the overall fall direction (see section 2.2) for the slip direction of the trial surface. (Numeric).

4.4.1.1.9.3. File Search

If ***srch*** = 'file' (or 'FILE') then the horizontal pattern of the search lattice is defined by a search grid file (section 4.4.2.1.3). This option can be useful if the user wants to restrict the search-lattice space to cover an irregular space rather than a box. With this option, **DO NOT** include the parameter-line pair:

LINE ID: `ismin jsmin ismax jsmax nsrchres`

Instead, include the parameter-line pair:

LINE ID: `ismin jsmin nsrchres`

These parameters are explained previously (section 4.4.1.1.9.1). Note that ***ismin*** and ***jsmin*** indicate the starting node of the search lattice defined in the search file, relative to the DEM. The maximum dimensions of the search array (***ismax*** and ***jsmax***) are defined by the dimensions of the search file as specified in the header lines of the file. The file indicates which horizontal nodes to include in the search lattice. If the user selects a coarse-to-fine search (***irefine*** = 1), the search grid file controls the horizontal limits of the initial coarse lattice. Subsequent finer searches will not be restricted by the search grid file.

The file search option requires two additional parameter-line pairs. A third parameter-line pair, ***irefine***, is optional. These parameters are described in section 4.4.1.1.9.1.

LINE ID: `zsmin zsmin zsrchres`

LINE ID: `irefine multres fostol`

LINE ID: `dr deginc degmax numdir`

4.4.1.1.10. Potential Failure Size Controls

REQUIRED when ***srch*** = 'box' (or 'BOX') or 'file' (or 'FILE'). NOT REQUIRED when ***srch*** = 'single' (or 'SINGLE').

LINE ID: `vacriterion armin armax vmin vmax tol limcol`

vacriterion specifies whether volume or horizontal surface area is the primary criterion controlling potential failure size. Scoops3D only analyzes potential failures within user-specified size limits. 'V' (or 'v') indicates that the primary size criterion is volume; 'A' (or 'a') indicates that it is horizontal surface area. For example, if volume is the primary criterion, the first potential failure mass at each search-lattice node must fall within the range of ***vmin*** to ***vmin*** + ***tol*** (parameters described below). Then, using area as the secondary criterion, Scoops3D checks that the area is between ***armin*** and ***armax*** (if not, Scoops3D proceeds to the next trial sphere). Each subsequent trial sphere increases in radius by ***dr*** until either ***vmax*** or ***armax*** is exceeded, or the trial surface intersects the DEM boundary. Although the primary criterion sets the minimum and maximum size limits, for a trial surface to be analyzed it must also fall within the secondary criterion size limits. **If the user does not want the secondary criterion to affect trial surface selection, the minimum and maximum secondary limits should be set equal to zero. Note that Scoops3D-i only uses one size criterion and automatically sets the secondary criteria size limits to zero.** The primary size control determines the name of the critical size output file (volume or area, see section 4.5.1.3) associated with the critical surfaces found during a Scoops3D analysis. (Character, 'v', 'V', 'a', or 'A').

armin, armax the minimum and maximum horizontal surface area limits for potential failure masses to be analyzed, given in area units consistent with the length units of the DEM. The area of the potential failure mass must fall in this range for a trial surface to be considered valid. If the user does not want area to restrict potential failure size when area is the secondary criterion, set both ***armin*** and ***armax*** = 0. (Numeric).

vmin, vmax the minimum and maximum volume limits for potential failure masses to be analyzed, given in volume units consistent with the length units of the DEM. The volume of the potential failure mass must fall in this range for a trial surface to be considered valid. If the user does not want volume to restrict potential failure size when used as the secondary criterion, set both ***vmin*** and ***vmax*** = 0. (Numeric).

tol the volume or area tolerance level used when computing an initial potential failure size at each search-lattice node, given in units consistent with the primary size control criterion. For example, if ***vacriterion*** = 'v' (or 'V'), the volume of the initial potential failure mass must fall between ***vmin*** and ***vmin*** + ***tol***. If ***tol*** is very small, Scoops3D may take more computational time to find an initial radius, or may not be able to find an initial radius within the volume or area range because of the discrete nature of the problem (for example, the volume does not change continuously with change in radius). We have found that a tolerance set to 10 percent of the minimum value for the primary size criterion usually works well. (Numeric, > 0).

limcol the preferred minimum number of active DEM columns to be included in a potential failure mass. If the number of active columns in a potential failure mass is less than ***limcol***, Scoops3D generates a message in the summary output file and creates an output file, *<filein>_ncolerr_out.txt*, with location and column information about the masses (section 4.5.2.2). However, Scoops3D does not halt computation using that trial surface if the mass contains less than ***limcol*** number of active columns. Our tests show that a potential failure mass with at least ~200 active columns commonly provides good estimates of factor of safety and volume, but masses with fewer active columns (~100) may still allow calculation of a factor of safety within a few percent of results with many active columns. Some situations, such as very steep terrain or purely cohesive strength, may require 300 to 500 active columns to provide good estimates (see sections 5.3.4 and 6.6) (Integer, > 0).

4.4.1.1.11. Output Options

Note that the Scoops3D output files listed below use the main parameter input file name (without extension) as a prefix, denoted *<filein>* in the following text.

4.4.1.1.11.1. Create New DEM File

NOT REQUIRED.

This option creates a new DEM file with selected potential failure masses removed.

LINE ID: `remove foscut`

remove character flag to control the creation of a new DEM (<filein>_newDEM_out.asc) with select potential failure masses removed. If ***remove*** = 'A' (or 'a'), all potential failure masses with a computed factor of safety (*F*) less than the ***foscut*** value are removed and an additional output file listing these surfaces, *<filein>_spheresltcut_out.txt*, is created. If ***remove*** = 'L' (or 'l'), the largest potential failure mass with *F* < ***foscut*** is removed. If ***remove*** = 'M' (or 'm'), only the potential failure mass with the overall lowest factor of safety (global minimum) is removed, provided F < ***foscut***. If ***remove*** = 'N' (or 'n') or is not specified or no potential failure masses have F < ***foscut***, then no new DEM is created. (Character, 'A', ' a', 'L', ' l', 'M', 'm', 'N', or 'n').

foscut factor of safety cut-off value for creating a new DEM with potential failure masses removed. (Numeric, > 0).

4.4.1.1.11.2. Create Search Quality Files

NOT REQUIRED.

This option creates three or four (four if ***srch*** = 'box') additional output files for examining the quality of the stability solutions and the DEM search. These files are grids in ASCII raster format and their contents are described in section 4.5.3.2.

LINE ID: `isqout`

isqout flag to create three or four search quality files. If ***isqout*** = 1, Scoops3D generates additional output files *<filein>_critcheck_out.asc, <filein>_numcols_out.asc, <filein>_searchgrid_out.asc*, and *<filein>_boundcheck_out.asc*. (Integer, 0 or 1).

4.4.1.1.11.3. Create Relative Factor-of-Safety File

NOT REQUIRED.

This option creates an additional output file containing a grid of the relative, or normalized, factor of safety (F_{rel}) for each DEM cell, defined as $F_{rel} = F/F_{min}$, where F_{min} is the lowest overall (global minimum) F found in the search.

LINE ID: `irelfos`

irelfos flag to create an output file containing the relative factor of safety for each DEM cell. If ***irelfos*** = 1, Scoops3D generates the file *<filein>_fos3drel_out.asc*. (Integer, 0 or 1).

4.4.1.1.11.4. Create 3D Search-Lattice File Highlighting Critical Nodes

NOT REQUIRED.

This option creates a 3D output file containing the minimum factor-of-safety (F) value found for each critical node in the 3D search lattice above the DEM. Critical nodes are the centers for the critical surfaces affecting the DEM. Search-lattice nodes with no associated critical surface are assigned a null value (section 4.5.3.4.1). Note that Scoops3D always creates a file containing a raster grid of the minimum factor-of-safety (critical) values for each DEM cell (*<filein>_fos3d_out.asc*).

LINE ID: `icritlattice`

icritlattice flag to create a 3D output file highlighting the critical nodes in the search lattice. If ***icritlattice*** = 1, Scoops3D generates the output file *<filein>_critfoslattice_out.3D*. The file contains the x, y, z coordinates and minimum factor of safety for each critical node in the search lattice. The coordinates are specified in the coordinate system of the DEM. This file may become large depending on the nodal spacing and extent of the search lattice. (Integer, 0 or 1).

4.4.1.1.11.5. Create 3D Search-Lattice File of Minimum F Value For Each Search Node

NOT REQUIRED.

This option creates a 3D file containing the minimum factor-of-safety (*F*) value found at each node searched in the 3D search lattice above the DEM. Note that the minimum found at each search lattice node may not necessarily correspond to a critical surface affecting the DEM, thus the contents of this file may differ from the critfoslattice file (section 4.4.1.1.11.4).

LINE ID: `ilattice`

ilattice flag to create an output file containing the minimum factor of safety computed at each search-lattice node. If ***ilattice*** = 1, Scoops3D generates the output file *<filein>_foslattice_out.3D*. The file contains the x, y, z coordinates and minimum factor of safety for each node in the search lattice. The coordinates are specified in the coordinate system of the DEM. This file may become large depending on the nodal spacing and extent of the search lattice. (Integer, 0 or 1).

4.4.1.1.11.6. Create Subsurface Minimum F File

NOT REQUIRED.

This option creates a 3D file containing the computed minimum factor-of-safety (*F*) values at defined points in the subsurface beneath the DEM.

LINE ID: `isubsurf zfrac`

isubsurf flag to create a 3D output file containing minimum factor-of-safety values in the subsurface. If ***isubsurf*** = 1 or 2, Scoops3D generates the output file *<filein>_subsurf_out.txt* with the location coordinates specified in either ijk (***isubsurf*** = 1) or xyz (***isubsurf*** = 2) format. If ***isubsurf*** = 3, the file *<filein>_subsurf_out.3D* with xyz coordinates and a simplified header in Point3D format is generated (see fig. 4.38 for example of Point3D format). The x and y coordinates are specified in the coordinate system of the DEM. The horizontal spacing of data within the file is equal to the DEM cell size; the vertical (depth) spacing is controlled by ***zfrac***, as described below. (Integer, 0, 1, 2, or 3).

zfrac fraction of the DEM cell size used to determine vertical spacing of the subsurface 3D factor-of-safety output file. Take care using this parameter, because the output file can become extremely large! Typical values are 0.5 or 1. A value of ***zfrac*** > 1 is recommended when the DEM resolution is known to be finer than necessary (section 5.1). (Numeric, > 0).

4.4.1.1.12. List of Additional Input Files

REQUIRED.

The last lines of the main parameter input file list the additional input files needed. A DEM file is always required, other files may be required depending on the parameters selected. The files names are entered as line pairs, with an identification line first and the file name second. File names may be specified with either relative or full pathnames, with delimiters (for example "/" or "\") appropriate for the computer operating system. See figures 4.15 and 4.16 and chapter 7 for some examples. The file formats and contents of the additional input files are described in section 4.4.2.

LINE ID: `DEM file`

<pathname/filename>

LINE ID: `search file`

<pathname/filename>

LINE ID: `pressure head file`

<pathname/filename>

LINE ID: `layer file`

<pathname/filenameprefix>

LINE ID: `material properties file`

<pathname/filename>

LINE ID: `piezometric file`

<pathname/filename>

Note that the specification of multiple property layers requires layer files with a common prefix. There must be a file for each layer (except the lowermost layer) with a numbered extension after the given root name, representing the layer number. The number of layer files should equal ***nmat***-1. For example, if ***layer file*** =

<pathname>/layer and ***nmat*** = 4, the specified pathname directory should contain the files: *layer_1.asc, layer_2.asc, and layer_3.asc* (section 4.4.2.1.4). A homogeneous problem (where ***nmat*** = 1) does not require layer files.

4.4.1.1.13. Output Directory Pathname

NOT REQUIRED.

This line pair identifies the pathname of the directory where all Scoops3D output files are placed during a run. If this option is specified without using Scoops3D-i, the user must ensure that this output directory already exists. If this line is omitted, all output files are placed in the directory containing the main parameter input file. Note that Scoops3D-i always creates a subdirectory under the directory containing the main parameter input file with the name *<filein>_output*.

LINE ID: `output directory`

<pathname/outputdirectoryname>

4.4.2. Additional Input Files

In addition to the main parameter input file, a Scoops3D analysis always requires a separate file containing the DEM. Depending on the options selected, other files may be needed as well. The additional input files are in either an Esri ASCII raster format (grid data) or 3D format for Scoops3D (table 4.1).

4.4.2.1. Grid Data

All grid files (DEM, search grid, layer, and piezometric surface files) contain a 2D array of values preceded by six required header lines (fig. 4.20). Grid files use the Esri ASCII raster format. The header lines contain the number of cells in the x direction (ncols, integer value), the number of cells in the y direction (nrows, integer value), the x coordinate of the lower left corner (xllcorner, numeric value), the y coordinate of the lower left corner (yllcorner, numeric value), the grid spacing (cellsize, numeric value), and the value for null cells (NODATA_value, numeric value). **At least 12 characters or spaces must precede data values in each of the six header lines.**

The 2D array of data following the header lines may be in free format, but there must be nrows number of lines, each containing ncols number of values. The values are written in the file exactly as they would appear in map (plan) view. Each value in the data array represents a uniform cell. **The coordinate system of the grid files must be projected into a rectilinear coordinate system (NOT latitude, longitude). Grid files of elevation (DEM, layers, and piezometric surfaces) must have the same horizontal and vertical length units.** For example, DEMs commonly use the UTM (Universal Transverse Mercator) coordinate system with vertical length units of meters.

An excerpt from a DEM file in Esri ASCII raster format shows the six required header lines (fig. 4.20). Here, the DEM has 96 columns (ncols), 91 rows (nrows), and 100 m resolution (cellsize). The values for xllcorner, yllcorner are the x and y coordinates of the origin at the lower left corner of the DEM in the UTM (Universal Transverse Mercator) coordinate system. The values following the header lines represent the ground-surface elevation (in meters) for 100 by 100 m grid cells. The elevations are written in the file exactly as they would appear in map view, in other words, the upper left elevation in the file (950.2679 m) corresponds with the elevation of the upper left (northwest) cell displayed on a map.

```
ncols     96
nrows     91
xllcorner   557974.631687
yllcorner   5111446.1291019
cellsize   100
NODATA_value -9999
950.2679 954.3484 1008.63 1005.364 1009.342 1010.104 1015.683 ....
958.0488 961.4271 1014.83 1020.795 1018.986 1016.861 1016.05 ....
972.327 971.7813 996.9572 1041.421 1029.844 1033.345 1031.922 ....
977.8392 979.4543 988.1952 1047.295 1046.076 1042.628 1047.686 ....
986.4683 992.5452 998.5279 1001.354 1062.244 1053.514 1059.542 ....
...
```

Figure 4.20. Text excerpt from a DEM file in Esri ASCII raster format. Example taken from the Mount St. Helens 100 m DEM (file name: *sthel_res100mDEM.asc* – see section 7.6).

The DEM coordinates of the lower left corner (xllcorner, yllcorner) are used in Scoops3D as a check that any additional input grid files have a consistent origin, or in the case of the search grid, that the search extent aligns with the DEM as intended. The coordinates for the lower left corner also define the coordinate system used to specify the coordinates of the trial surface center for a single surface search (section 4.4.1.1.9.2).

The dimensions (ncols and nrows), cell size, and lower left corner must be the same for all grid files associated with a Scoops3D run (with the exception of the search grid, see section 4.4.2.1.3). The NODATA value can vary between different input grids. If the lower left coordinates are unknown, Scoops3D allows the substitution of other values, such as xllcorner = 0, yllcorner = 0, provided all grids for a particular analysis have the same origin.

4.4.2.1.1. Tips for Esri ArcGIS users

If users have access to Esri ArcGIS software, the grid input files for Scoops3D can be created in ArcToolbox with **Conversion tools >From Raster > Raster to ASCII** or in python scripting with "arcpy.RasterToASCII_conversion (<*in_raster*>, <*out_asciifile*>)". These specific commands function in ArcGIS 10.2 and are also available in older versions of ArcGIS.

4.4.2.1.2. Digital Elevation Model (DEM) Input File

REQUIRED.

This input file contains elevation values for each cell of the digital elevation model (DEM) in ASCII raster format (see for example, fig. 4.20).

4.4.2.1.3. Search File

REQUIRED ONLY if ***srch*** = 'file'.

This input file contains an integer array describing the horizontal (x, y) pattern of the search lattice. The search file option allows the user to specify an irregularly shaped, non-rectangular search lattice. The utility of a search file is illustrated in Seattle examples P and Q (section 7.5).

This file must be in ASCII raster format, containing the standard six-line header (see for example, fig. 4.20), and the cell size must be the same as the DEM. The values of ncols and nrows are used by Scoops3D to determine the maximum horizontal extent of the search array relative to ***ismin*** and ***jsmin*** (section 4.4.1.1.9.3). Note that this file does not affect the vertical (z) extent of the search lattice, which is determined by the control parameters ***zsmin***, ***zsmax***, and ***zsrchres*** in the main parameter input file (section 4.4.1.1.9.1).

Following the header lines, each line in this file must contain an entire row of values identifying which search-lattice locations are active. A positive integer indicates that the xy location of the corresponding cell center in the search lattice will be used in the search. A negative integer or zero eliminates the cell center location from use in the search lattice. The search file option is commonly used with the coarse-to-fine search refinement option turned off (***irefine*** = 0). However, if the user selects the coarse-to-fine search option (***irefine*** = 1), the values (positive versus negative) in the search file are used only for the initial coarse search. Subsequent finer searches are restricted only by the horizontal area bounded by the extent of the search file, not by the positive or negative values contained in the search file.

If needed, the search grid and DEM can have different values for ncols, nrows, xllcorner or yllcorner, allowing the search grid to be larger or smaller than the DEM extent. Calculate the xllcorner and yllcorner of the search grid relative to the DEM, using ***ismin*** and ***jsmin*** (shown in fig. 4.17) and the following equations:

$$\text{xllcorner}_{\text{searchgrid}} = \text{xllcorner}_{\text{DEM}} + (\boldsymbol{ismin}\text{-}1)\text{*cellsize, and} \quad (4.1)$$

$$\text{yllcorner}_{\text{searchgrid}} = \text{yllcorner}_{\text{DEM}} + (\boldsymbol{jsmin}\text{-}1)\text{*cellsize,} \quad (4.2)$$

where cellsize is the length of one side of a DEM cell.

If the DEM and search grid corner coordinates do not agree, Scoops3D issues a warning in the main output file, but will continue to execute.

4.4.2.1.4. Material Layer Files

REQUIRED ONLY if ***nmat*** > 1.

The material layer files define the bottom elevation of every DEM cell for each layer. These files must be in ASCII raster format, containing the standard six-line header (see for example, fig. 4.20). The header parameters ncols, nrows, xllcorner, yllcorner, and cellsize must be the same as the DEM. Elevations in the files must be in length units of the DEM. The total number of layers is defined by the parameter ***nmat*** in the main input file (see section 4.4.1.1.4.1). There must be one layer file for each material, **except for the final, lowest material.** Therefore, if there are 5 materials, there must be 4 layer input files. The 5th material is assumed to extend from the bottom of the lowermost (4th in this example) layer in the column to the depths of the earth. If only one layer is used in the main parameter input file (***nmat*** = 1), then no additional layer files are needed.

The layer files must have a root name in common, with a numbered extension representing the layer number, for example *layer_1.asc*, *layer_2.asc*, etc., where "*layer*" is the user-defined root name. The numbers of the layers must be in order of occurrence as if drilling vertically downward from the ground surface. If two layers are adjacent without any overlap, then the ordering of the two does not matter. If the layer boundaries occur in different order at different locations (for example, in the case of interfingering), more layer files must be created to define the sequence of bottom boundaries. A lower numbered layer file (meaning that it is closer to the ground surface) must never contain an elevation value that is less than the elevation value at the corresponding cell in a higher numbered (deeper) layer file.

Elevations in the layer files should be in length units of the DEM. **If a layer is discontinuous and does not occur at all DEM cells, each cell in the layer file with non-occurrence must be represented by the NODATA value.** The user can define discontinuous layers by setting the elevation of a layer equal to the elevation of the layer above. In this situation, Scoops3D will issue a warning and proceed with computations assuming that the lower layer has a thickness of zero at those locations (see examples in sections 7.2 and 7.3).

4.4.2.1.5. Piezometric Surface File

REQUIRED ONLY if ***water*** = ‘pz’ or ‘PZ’.

This input file contains elevation data (in length units of the DEM) for a piezometric surface, in ASCII raster format (see for example, fig. 4.20). The header parameters ncols, nrows, xllcorner, yllcorner, and cellsize must be the same as the DEM grid.

Following the header, each line in this file must contain an entire row of values designating the elevation of the piezometric surface at each DEM cell. **If a piezometric surface does not exist at every DEM node, each node with non-occurrence must be represented by the NODATA value.** For the stability calculations performed by Scoops3D, pore pressure at a point within a vertical column is computed as $\gamma_w z_{pz}$, where z_{pz} is the vertical depth below the elevation of the piezometric surface.

4.4.2.2. 3D Data

Options that utilize 3D data (3D distribution of pore-pressure head and (or) 3D material properties) require additional input files. These 3D input files contain header information, followed by a list of 3D location coordinates and the corresponding data. Typically, a user will need to manipulate 3D data derived from other models or sources into formats usable by Scoops3D by regridding, adding header lines, and making other changes as needed.

The 3D file formats for Scoops3D differ fundamentally from the format used for grid data (section 4.4.2.1). Instead of a 2D map-view array of values for each cell, the 3D files contain data for points beneath each DEM cell. Specifications for 3D data are:

- Horizontal coordinates should be located at the center of each DEM cell.
- 3D files must contain space-delimited or tab-delimited data for every active DEM cell (that is, all cells that do not contain the NODATA value).
- 3D files must contain data to the greatest depth that any trial surface may intersect. If any trial surface falls below the lowest defined 3D data point in a vertical column, Scoops3D issues an error and stops.
- Locations of the 3D data values may be specified using one of three different coordinate methods: ijk, xyz, and ijz. The coordinate specification method is defined in the header of the 3D file (section 4.4.2.2.1).
- Data must be listed sequentially in either ascending or descending vertical order for each active DEM cell. Data do not need to be listed sequentially in the horizontal directions.

- 3D data for material properties may be either linearly interpolated between data points or interpreted as discrete fixed blocks (sections 4.4.2.2.2 and 4.4.2.2.6). The method of interpretation is controlled by the parameter ***linterp*** in the main parameter input file (section 4.4.1.1.4.2). 3D pressure-head data are always linearly interpolated between data points.
- Optional descriptive comments must be located at the beginning of the file and designated by the character '#' at the beginning of the comment.

4.4.2.2.1. 3D Data Coordinates

Coordinates in the three orthogonal directions define the location of each 3D data value. The user can select one of three methods to specify the 3D coordinates (table 4.2). The xyz coordinate system is defined by the coordinate system of the DEM and the ijk coordinate system is defined as integer counters, where the point aligned with the center of the lower left cell of the DEM at the lowest elevation has values i = 1, j = 1, k = 1; i increases in the positive x direction, j increases in the positive y direction, and k increases in the positive z-direction upward (fig. 4.21). Scoops3D also allows a combination of the two coordinate systems (designated as ijz), where horizontal coordinates are defined as integer counters and vertical coordinates are in the DEM coordinate system. The ijz coordinates are useful for data defined as integer counters relative to the DEM cell numbers and containing irregular vertical (z) spacing. Examples of 3D files formatted for Scoops3D in ijz format are provided in the folder titled *examples* (Scoops3D examples C, E, I, and Q, sections 7.2, 7.3, and 7.5).

If the user's data is in discrete finite volumes or blocks, instead of point format, coordinates of points in or on the blocks are needed for the 3D input files formatted for Scoops3D (fig. 4.21*B*). The horizontal coordinates (x,y or i,j) are for the center of the block and the vertical coordinate (z or k) can be located on the top, center, or bottom of the block.

Table 4.2. List of methods for defining data coordinates for 3D files formatted for Scoops3D.

[The method is defined by the parameter ***coords*** in the header lines of the 3D file]

Coords	Horizontal coordinate system	Vertical coordinate system
xyz	DEM coordinate system	DEM coordinate system
ijk	Integer counters (relative to the lower left corner cell of the DEM)	Integer counter (relative to ***zmin***)
ijz	Integer counters (relative to the lower left corner cell of the DEM)	DEM coordinate system

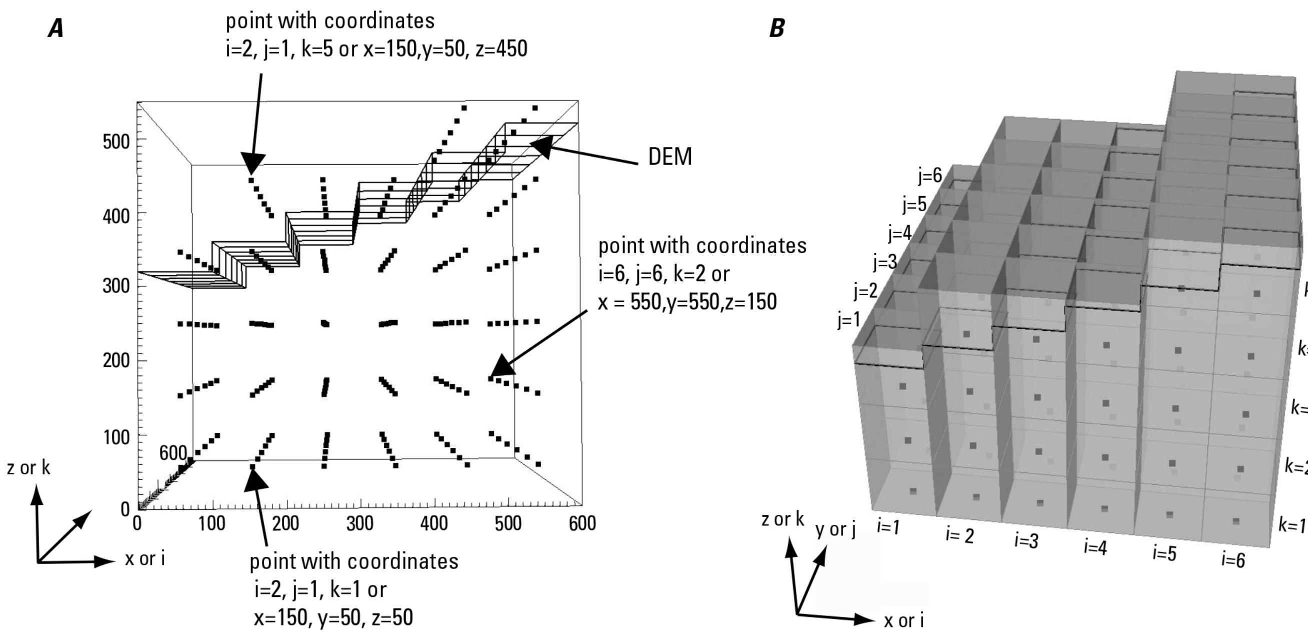


Figure 4.21. Diagrams illustrating 3D data portrayed with the xyz and ijk coordinate systems. *A*, 3D point data with axes labeled using the xyz coordinate system. Equivalent points in the ijk system are shown for comparison. Note that at least one data point above the DEM is required if the interpolation option is selected. *B*, 3D block labeled with the ijk coordinate system. In this case the locations of 3D points required by Scoops3D are shown at the bottom of each block (***zlocation*** = ‘bottom’). For illustrative purposes, these examples show sparse data and a low resolution DEM of constant slope. The DEM has the attributes: ncols = 6, nrows = 6, xllcorner = 0, yllcorner = 0, and cellsize = 100. In practice, the DEM and 3D input file used for Scoops3D should have a significantly larger number of data points.

4.4.2.2.2. 3D Data Representation

Scoops3D uses discrete columns based on the DEM raster cells for its stability analysis. The value of each 3D parameter (pore-pressure head or material properties) is horizontally uniform at any specific elevation within each column. In the vertical direction, Scoops3D assumes that pore-pressure heads vary continuously (linearly interpolated) between data points because pressure is usually a continuous field within earth materials. However, material properties (unit weight, angle of internal friction or cohesion) may vary continuously in the vertical direction or be fixed within discrete finite volumes (block data) (fig. 4.22). The user can select which method best represents their material property data by setting a flag (***linterp***) in the main parameter input file. Section 4.4.2.2.6 provides examples of these different interpretations and describes the additional header lines needed for block data.

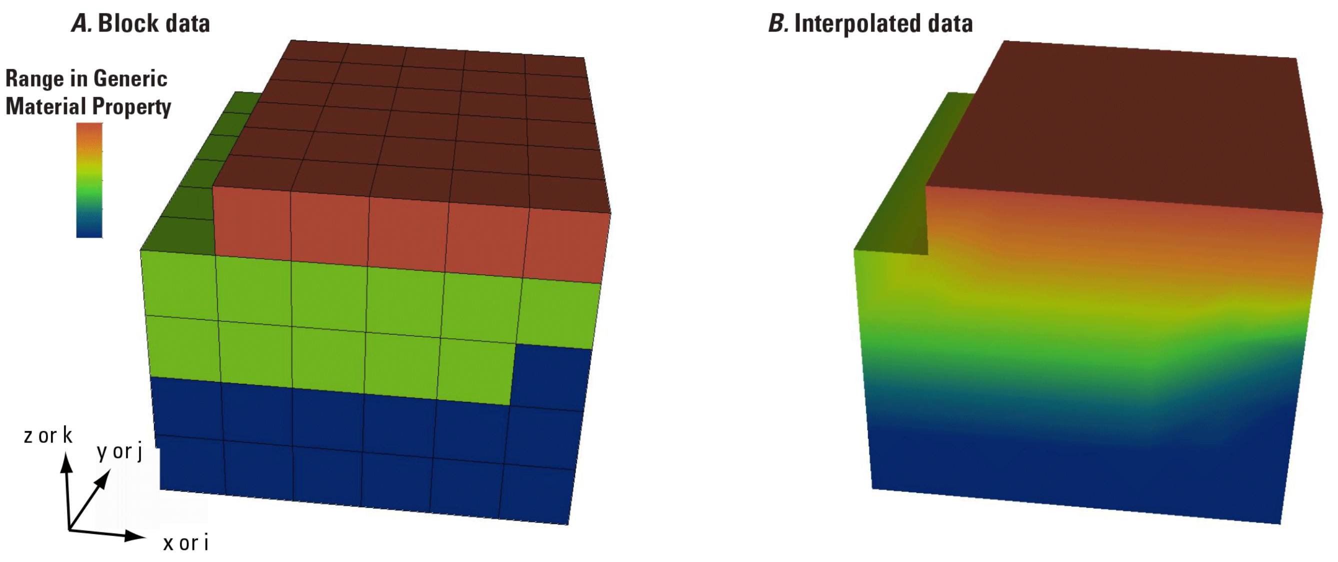


Figure 4.22. Diagrams illustrating the same generic 3D material property data interpreted as either discrete blocks or interpolated data. *A*, Data in discrete blocks (***linterp*** = 0). *B*, Interpolated data (***linterp*** = 1). Colors indicate different material properties. The two examples portray interpretations of 3D point data that are regularly spaced in the vertical (z) direction. For illustrative purposes, this example shows only a few 3D blocks. In practice, the DEM and 3D input file used for Scoops3D should have significantly larger number of 3D blocks.

4.4.2.2.3. 3D File Header Lines

Any number of descriptive comment lines, preceded by the character '#', may be included at the beginning of a 3D input file; these descriptor lines are ignored by Scoops3D. Following these optional descriptor lines, the 3D files must contain some parameter line pairs before the data lines. These line pairs identify important attributes of the data, such as format and spacing. All 3D files must contain the following line pair defining the data coordinate method:

LINE ID: `coords`

coords the method used to specify the spatial coordinates of the data (table 4.2, fig. 4.21). There are three options:

1. A designation of 'xyz' indicates that each data line contains x, y, z location coordinates in the coordinate system of the DEM and in length units of the DEM.
2. A designation of 'ijk' indicates that each data line is identified by integer counters, where i=1, j=1, and k=1 indicates the lowermost data point, located in the center of the lower left (southwest corner) cell of the DEM (horizontally) (fig. 4.21); 'ijk' data must be regularly spaced in the vertical direction. When

material properties are interpreted as block data (***linterp*** = 0), ***zmin*** (described below) defines the location of the top, center or bottom elevation of the lowermost block (defined by ***zlocation***, see section 4.4.2.2.6). Values of i increase in the positive x direction and j increase in the positive y direction until they reach their maximums at the values of ncols and nrows, respectively, for the DEM.

3. A designation of 'ijz' indicates that x and y locations are identified by integer counters and z locations are elevations in length units of the DEM. Note that the conversion from ij coordinates to xy for the exact location of the center of the DEM cell is:

$$x = (i-1)*cellsize + 0.5*cellsize + xllcorner, \text{ and} \tag{4.3}$$

$$y = (j-1)*cellsize + 0.5*cellsize + yllcorner, \tag{4.4}$$

where cellsize is the length of one side of a DEM cell.

Although it is desirable, Scoops3D does not require the xy coordinates in a 3D file to be precisely in the center of a cell. Scoops3D allows some flexibility to account for floating point errors in precision. Therefore, as long as the specified xy coordinates fall within the bounds of a DEM cell, the data specified for those coordinates are associated with that cell. (Character, 'xyz', 'ijk', or 'ijz').

If ***coords*** = 'ijk', then an additional two-parameter line pair is needed after the `coords` line pair. This line pair defines the vertical spacing and location of the regularly spaced data:

LINE ID: `delz zmin`

delz vertical (z) spacing between data values, in length units of the DEM. (Numeric, >0).

zmin lowest elevation of data in the 3D file, in length units of the DEM. (Numeric).

4.4.2.2.4. 3D Pressure-Head File or 3D Variably Saturated Pressure-Head File

REQUIRED ONLY if ***water*** = '3d', '3D', 'vg', 'VG', 'fx' or 'FX'.

3D pore-pressure heads (*h*) contained in this file are converted to pore pressures by Scoops3D to calculate a factor of safety. If any trial surface falls below the lowest defined 3D pressure-head point in a vertical column, Scoops3D issues an error and stops. Note that when computing pore pressure that acts on the base of a column, Scoops3D always interpolates between data values located at elevations vertically above and below the trial surface.

For 3D pressure-head data that are regularly spaced in the vertical direction, data can be presented in one of three forms: x,y,z,h , i,j,k,h, or i,j,z,h, where h represents the pressure head at the specified 3D coordinate (section 4.4.2.2.1). Examples of 3D pressure-head files are shown in figure 4.23. Data that are irregularly spaced in the z direction can only be presented in x,y,z,h or i,j,z,h formats.

A. Excerpt from a 3D pressure head file, *coords* = 'xyz':

```
# comment lines are preceded by a #
# 3D pressure head with xyz coordinates
# regular vertical spacing
# x y z h
coords
xyz
50 50 -100 50
50 50 -70  45
50 50 -40  10
50 50 -10 0
50 50 20 0
150 50 -100 50
...
```

B. Excerpt from a 3D pressure head file, *coords* = 'ijk':

```
# comment lines are preceded by a #
# 3D pressure head with ijk coordinates
# regular vertical spacing
# i j k h
coords
ijk
delz  zmin
 30 -100
1 1 1 50
1 1 2 45
1 1 3 10
1 1 4 0
1 1 5 0
2 1 1 50
...
```

C. Excerpt from a 3D pressure head file, *coords* = 'ijz':

```
# comment lines are preceded by a #
# 3D pressure head with ijz coordinates
# regular vertical spacing
# i j z h
coords
ijz
1 1 -100 50
1 1 -70  45
1 1 -40  10
1 1 -10 0
1 1 20 0
2 1 -100 50
...
```

Figure 4.23. Text excerpts from three files illustrating the three methods for specifying 3D pressure-head data that are regularly spaced in the vertical (z) direction. These examples use equivalent data and the DEM has xllcorner = yllcorner = 0 and cellsize = 100 m. The lowest vertical elevation (***zmin***) for the pressure-head data is 100 m and the spacing between data points in the vertical (***delz***) is 30 m. *A,* 'xyz' format. xy coordinates are located in the center of the DEM cell. *B,* 'ijk' format. Note that i = 1,j = 1,k = 1 corresponds to lowest vertical elevation in the center of the DEM cell in the lower left corner of a map view. *C,* 'ijz' format.

4.4.2.2.5. 3D Variably Saturated Pressure-Head and Water Content File

REQUIRED ONLY if ***water*** = ‘vs’ or ‘VS’.

This 3D file contains values for both variably saturated pressure head (positive or negative relative to atmospheric pressure) and water content. Section 2.4 describes how Scoops3D uses these values to calculate the factor of safety. If any trial surface falls below the lowest defined 3D point in a grid cell, Scoops3D issues an error and stops.

For 3D variably saturated pressure-head data that are regularly spaced in the vertical direction, data can be presented in one of three forms: x,y,z,h,theta, i,j,k,h,theta, or i,j,z,h,theta, where h represents the pressure head (h) (negative where it represents matric suction) and theta represents the water content at the specified 3D coordinate (fig. 4.24). Coordinate systems (xyz, ijk, ijz) are described in section 4.4.2.2.1. Data that are irregularly spaced in the z direction can only be presented in x,y,z,h,theta or i,j,z,h,theta formats.
The USGS model TRIGRS (Baum and others, 2008) can generate a 3D file of variably saturated pressure-head and water content data for use by Scoops3D.

4.4.2.2.6. 3D Material Properties File

REQUIRED ONLY if ***str3d*** = 1.

This 3D file can contain any or all of the material properties parameters: cohesion (c), angle of internal friction (ϕ), total unit weight (γ_t), partially saturated unit weight (γ_{ps}), and saturated unit weight (γ_s); the units weights required depend on the groundwater option chosen (see section 4.4.1.1.4.1 for possible combinations). Material property data must be in units consistent with the DEM. Each parameter must be completely defined in either this 3D file (with values for each location) or as uniform values in the main parameter input (.scp) file. Any parameters included in the 3D file must be assigned a value of -1 in the ***lnum*** line in the main parameter input file (see section 4.4.1.4.2). Values not included in the 3D file are assumed to be uniform and are assigned the value specified in the ***lnum*** line. If any trial surface falls below the lowest defined 3D point in a vertical column, Scoops3D issues an error and stops.

Data in 3D files formatted for Scoops3D are described as points in a 3D domain (figs. 4.25*A*, 4.26, and 4.27). For material properties, Scoops3D can interpret these 3D points in one of two ways, designated by the user: (1) the points represent a continuously varying field (***linterp*** = 1) where Scoops3D uses linear vertical interpolation between data points (fig. 4.25*B*) or (2) the points represent locations defining the extent of discrete fixed blocks (***linterp*** = 0) where Scoops3D assumes uniform properties within the block (fig. 4.25*C* and *D*). The user controls the method of interpretation by setting ***linterp*** in the main parameter input file (see section 4.4.1.1.4.2).

Excerpt from 3D variably saturated pressure head file, *coords* = 'ijz':

```
# Comments: Quasi-3D pressure head data from TRIGRS, v. 2.0.10e
# TRIGRS, clipped area of North Charlotte Creek, Oregon
# i j z h th
# timestep=       1
# time=     0.0000000
coords
ijz
   1  704   251.96   -2.365   0.8676E-01
   1  704   251.85   -2.277   0.8761E-01
   1  704   251.73   -2.188   0.8862E-01
   1  704   251.62   -2.099   0.8981E-01
   1  704   251.50   -2.010   0.9122E-01
   1  704   251.39   -1.921   0.9288E-01
   1  704   251.28   -1.831   0.9485E-01
   1  704   251.16   -1.742   0.9717E-01
   1  704   248.95   0.0000   0.4700
   1  704   201.96    29.14   0.4700
   2  704   251.18   -2.324   0.8703E-01
   2  704   251.08   -2.242   0.8786E-01
   2  704   250.98   -2.161   0.8882E-01
   2  704   250.87   -2.079   0.8995E-01
   2  704   250.77   -1.997   0.9126E-01
   2  704   250.66   -1.915   0.9280E-01
   2  704   250.56   -1.833   0.9459E-01
   2  704   250.45   -1.751   0.9668E-01
   2  704   248.23   0.0000   0.4700
   2  704   201.18    29.32   0.4700
   3  704   250.41   -2.217   0.8965E-01
   3  704   250.31   -2.145   0.9069E-01
   3  704   250.22   -2.072   0.9188E-01
   3  704   250.12   -2.000   0.9324E-01
   3  704   250.03   -1.927   0.9478E-01
   3  704   249.93   -1.854   0.9654E-01
   3  704   249.84   -1.782   0.9854E-01
   3  704   249.74   -1.709   0.1008
   3  704   247.52   0.0000   0.4700
   3  704   200.41    27.81   0.4700
...
```

Figure 4.24. Text excerpt from a 3D variably saturated pressure-head file containing data that are irregularly spaced in the vertical (z) direction. Coordinates are specified as 'ijz'. Values of pressure head and water content are listed for each point.

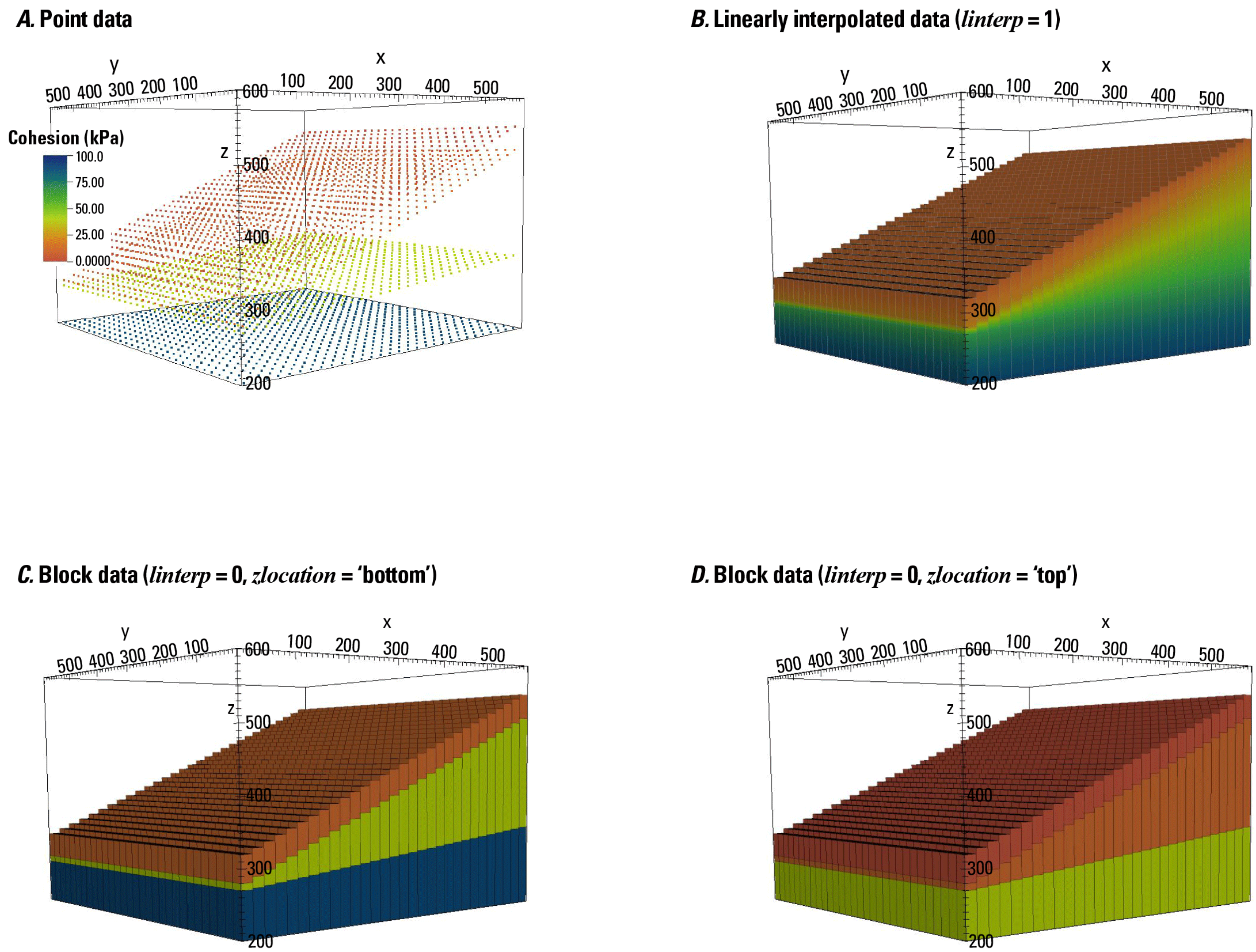


Figure 4.25. Sequence of diagrams showing perspective views with different interpretations of 3D cohesion data. *A*, locations of 3D points and cohesion values contained in a 3D material property file for Scoops3D (fig. 4.26*A*), *B*, linearly interpolated data (***linterp*** = 1), *C*, block data (***linterp*** = 0) with ***zlocation*** = 'bottom', *D*, block data (***linterp*** = 0) with ***zlocation*** = 'top'. 3D perspective images created using VisIt software.

If data are best represented as fixed within blocks (***linterp*** = 0), then the z-coordinate of the data represents the location of a data point at the top, center, or bottom of the block. Scoops3D will attribute material properties to a trial surface depending on which block contains that surface. Figures 4.26 and 4.27 show examples of 3D material properties files with irregularly and regularly spaced data. If ***linterp*** = 0, the 3D material properties file requires an additional header line pair containing one parameter:

LINE ID: `zlocation`

zlocation the vertical location of the specified parameter values within a 3D block. The location can be 'top', 'center', or 'bottom' (table 4.3). All values in the horizontal (x and y) directions should be located in the center of the DEM cell. The selection of the option ***zlocation*** = 'center' is only allowed when the data have regular vertical spacing. The ***zlocation*** line pair is not required if ***coords*** = 'ijk' (***zmin*** should define the elevation of the bottom of the lowest cell), and it is ignored for linearly interpolated data (***linterp*** = 1). (Character, 'top', 'center,' 'bottom').

Table 4.3. List of valid values for ***zlocation*** when 3D material property data are represented as block data.

[In these cases ***linterp*** = 0]

Coords	Valid values for ***zlocation***	
	Vertical spacing	
	regular	irregular
xyz	'top', 'center' or 'bottom'	'top' or 'bottom'
ijz	'top', 'center' or 'bottom'	'top' or 'bottom'
ijk	Not required	Not required

A. Excerpt from 3D material property file containing cohesion data, *coords* = ‘ijz’, irregular vertical spacing:

```
# 3D material property file
# i j z cohesion
coords
ijz
  1 1 200.000 90
  1 1 270.000 40
  1 1 280.000 10
  1 1 320.000 0
  2 1 200.000 90
  2 1 272.000 40
  2 1 288.000 10
  2 1 328.000 0
  3 1 200.000 90
  3 1 274.000 40
  3 1 296.000 10
  3 1 336.000 0
  4 1 200.000 90
  4 1 276.000 40
...
```

B. Associated line pairs required in the main parameter input file:

```
str3d linterp
1 1
nmat
1
lnum  cee  phi  gamt
1 -1  30.  24.
```

Figure 4.26. Text excerpts from two files showing 3D data formats and additional parameters needed for 3D data shown in figure 4.25. *A*, Excerpt from the 3D material properties file displayed in figure 4.25. This file contains cohesion data and is irregularly spaced in the vertical (z) direction. *B*, Additional line pairs required in the main parameter input file for the linear interpolation (***linterp*** = 1) of cohesion displayed in figure 4.25*B*. Here ***cee*** = -1 indicates that the cohesion data are listed in the specified 3D data file (excerpted in *A*), and the other material parameters are constant. With this option, Scoops3D linearly interpolates to determine cohesion on the trial surface for each column.

Excerpt from 3D material properties file, *coords* = 'ijk', regular vertical spacing:

```
# 3D material properties file
# Donald and Giam (ACADS) example 1c
# regular vertical spacing, ijk coordinates
#
# i j k cee  phi  gamt
#
coords
ijk
delz zmin
1 12
  1 1 1 7.20000 20.0000 19.5000
  1 1 2 7.20000 20.0000 19.5000
  1 1 3 7.20000 20.0000 19.5000
  1 1 4 7.20000 20.0000 19.5000
  1 1 5 7.20000 20.0000 19.5000
  1 1 6 7.20000 20.0000 19.5000
  1 1 7 7.20000 20.0000 19.5000
  1 1 8 7.20000 20.0000 19.5000
  1 1 9 7.20000 20.0000 19.5000
  1 1 10 7.20000 20.0000 19.5000
  1 1 11 7.20000 20.0000 19.5000
  1 1 12 7.20000 20.0000 19.5000
  1 1 13 7.20000 20.0000 19.5000
  1 1 14 7.20000 20.0000 19.5000
  2 1 1 7.20000 20.0000 19.5000
  2 1 2 7.20000 20.0000 19.5000
...
```

Figure 4.27. Text excerpt from a 3D material properties file with data regularly spaced in the vertical (z) direction. The file contains all of the material properties required: cohesion (***cee***), angle of internal friction (***phi***), and total unit weight (***gamt***). Scoops3D example I (section 7.3) uses irregularly spaced material property data equivalent to this file.

4.5. Program Output

During execution, Scoops3D generates a suite of output files including:

- Six standard output files that are always produced.
- Six conditional output files that are created depending on user-selected options or the existence of errors and filters related to the factor-of-safety calculations.
- Nine optional output files (table 4.4).

The user can control the creation of any or all of the nine optional output files using flags in the main input file (see section 4.4.1.1.11). Each output file is created in a form appropriate for the data type, either as a text, ASCII raster grid format, or 3D file.

Table 4.4. Description of Scoops3D output files including file names, conditions for creation, and null values.

[Null values are equivalent to NODATA values for grid files. Output files contain three possible types of data: (1) text – a text summary or listing of information, (2) grid – raster grid data in Esri ASCII format, or (3) 3D – listing of 3D coordinates and associated factor-of-safety (*F*) values]

Section	File suffix[1]	Criteria for creation of file	Data type	Null value	Description
Standard output files (always produced)					
4.5.1.1	*_out.txt*	Always	Text	---	Summary output file - echoes input parameters and describes overall minimum *F*
4.5.1.2	*_fos3d_out.asc*	Always	Grid	9999	Minimum 3D *F* for each DEM cell with the user-specified slope-stability method
4.5.1.3	*_fosvol_out.asc* or *_fosarea_out.asc*	***vacriterion*** = 'V' or 'v' or ***vacriterion*** = 'A' or 'a'	Grid	-9999	Volume (or area) of the critical surface for each DEM cell. One file is generated depending on the value of ***vacriterion***
4.5.1.4	*_spheres_out.okc*	Always	Text	---	Parameters associated with minimum *F* for each DEM cell
4.5.1.5	*_slope_out.asc*	Always	Grid	-9999	Slope of ground surface at each DEM cell
4.5.1.6	*_errors_out.txt*	Always	Text		Errors related to input files
Conditional output files (warning, filtering, and debugging - sometimes produced)					
4.5.2.1	*_ordfos3d_out.asc*	***method*** = 'B' or 'b'	Grid	9999	3D Ordinary (Fellenius) *F* for critical surface identified by Bishop's method for each DEM cell
4.5.2.2	*_ncolerr_out.txt*	Failure masses with fewer columns than ***limcol***	Text	---	Parameters associated with trial surfaces analyzed with columns less than user-specified value
4.5.2.3	*_filter_out.txt*	Non-converging or filtered surfaces	Text	---	Parameters associated with trial surfaces that were filtered out or had non-convergent solutions
4.5.2.4	*_filtergrid_out.asc*	Non-converging or filtered surfaces	Grid	-9999	Number of times each DEM cell had trial surfaces that were filtered out or had non-convergent solutions
4.5.2.5	*_foslocal_out.txt*	***method*** = 'O' or 'o', and ***srch*** = 'single'	Text	---	Local driving and resisting forces, and *F*, for each DEM cell on a user-specified trial surface
4.5.2.6	*_spheresltcut_out.txt*		Text	---	Parameters associated with trial surfaces with *F* less than a user-specified cutoff value (***foscut***)

Section	File suffix[1]	Criteria for creation of file	Data type	Null value	Description
Optional output files (user-selected)					
4.5.3.1	*_newdem_out.asc*	***remove*** = ‘A’, ‘a’, ‘L’, ‘l’, ‘M’, or ‘m’	Grid	-9999	DEM with user-specified potential failure masses removed
4.5.3.2.1	*_critcheck_out.asc*	***isqout*** = 1	Grid	-9999	Check on the volumes or areas associated with the critical surfaces
4.5.3.2.2	*_numcols_out.asc*	***isqout*** = 1	Grid	-9999	Number of columns associated with the critical surface at each DEM cell
4.5.3.2.3	*_searchgrid_out.asc*	***isqout*** = 1	Grid	-9999	Location of horizontal search space relative to the DEM
4.5.3.2.4	*_boundcheck_out.asc*	***isqout*** = 1 and ***srch*** = 'box'	Grid	-9999	Check on the search-lattice boundaries
4.5.3.3	*_fos3drel_out.asc*	***irelfos*** = 1	Grid	9999	3D relative *F* for each DEM cell
4.5.3.4.1	*_critfoslattice_out.3D*	***icritlattice*** = 1	3D	---	Minimum *F* for critical surface found at each search-lattice node
4.5.3.4.2	*_foslattice_out.3D*	***ilattice*** = 1	3D	---	Minimum *F* found at each search-lattice node
4.5.3.5	*_subsurffos_out.3D or _subsurffos_out.txt*	***isubsurf*** = 3 or ***isubsurf*** = 1 or 2	3D	---	Minimum *F* at and beneath each DEM cell

[1]File names start with input file root name <*filein*>, followed by the file name suffix listed in this table.

All output file names begin with the main input file root name (for example, if the main input file is *file1.scp*, then the main output file is called *file1_out.txt*). All output files are created in the output directory designated in the main Scoops3D input file. If no output directory is specified, then the output files can be found in the same directory as the main parameter input file. In the discussion below, we identify the output files using the root name plus a descriptive file suffix (table 4.4), with <*filein*> serving as a proxy for the root name of the main parameter input file.

Although some output files can be viewed in a text editor, thorough analysis of the output files from Scoops3D requires additional software such as a GIS or 3D visualization software. This manual shows examples of images produced using Esri ArcMap (http://www.esri.com/software/arcgis), VisIt (open source software developed by the U.S. Department of Energy, https://wci.llnl.gov/codes/visit/about.html), and QGIS (http://www.qgis.org) software. Other software packages with GIS, 2D, or 3D visualization capabilities can be used, although some software will require file format conversion.

4.5.1. Standard Output Files

These output files are always produced upon completion of a successful Scoops3D run.

4.5.1.1. Main Output File

NAME: <*filein*>*_out.txt*
FORMAT: text

This output file echoes the parameters contained in the main input file with explanatory text, lists the names of the output files generated, the number of trial surfaces analyzed, and contains results about the overall or global minimum factor of safety found during the Scoops3D run. Note that the slip direction for the global minimum is an angle measured from 0° along the positive x-axis, and positive in the counter-clockwise direction. An example of the main output file is shown in figure 4.28.

```
    *************************************************************
                                Scoops3D
          3D Slope Stability Throughout a Digital Landscape
                         U.S. Geological Survey
                             Version: 1.0
    *************************************************************


This file: R_sthel_output\R_sthel_out.txt

Start date and time: 07/11/2014  10:24:06
Description: Scoops3D example R; Mount Saint Helens

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
I. INPUT FILES:
  DEM file: input\sthel_res100mDEM.asc
  Main parameter input file: R_sthel.scp

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
II. SIMULATION PARAMETERS:
------------
DEM
Input file for topography: input\sthel_res100mDEM.asc
  Dimensions of DEM grid (x,y):                                      96    91
  Number of cells in DEM grid:                                          8736
  Number of non-null cells in DEM grid:                                 8668
  Horizontal resolution of DEM grid (m ):                             100.00
  Minimum elevation of DEM (m ):                                     743.277
  Maximum elevation of DEM (m ):                                    2928.884
  xllcorner and yllcorner (m ):                     557974.632    5111446.129
------------
UNIT DESCRIPTORS (used for labels in output files)
lengthunits   ceeunits    gammaunits
     m          kPa         kN/m^3
------------
MATERIAL PROPERTIES
Property method:                                                       layer
Number of layers (nmat):                                                   1
                      total unit wt.
lnum   cee      phi      gamt
       kPa              kN/m^3
  1   1000.00  40.000   24.000
------------
GROUNDWATER CONFIGURATION
Groundwater method (water):                                             None
------------
EARTHQUAKE LOADING
Horizontal pseudo-acceleration coefficient (dimensionless)(eq):        0.000
------------
LIMIT-EQUILIBRIUM METHOD
Analysis method (method):                                             Bishop
------------
SEARCH METHOD (srch)                                                     box
POTENTIAL FAILURE SIZE CONTROLS
Primary constraint, volume or area (vacriterion):                     Volume
Surface area is not a criterion for size restriction.

Volume range of potential failures (m ^3)(vmin, vmax):     1.000E+08 3.500E+09
Tolerance amount for initial potential failure (tol):               1.000E+07
Minimum number of active columns in potential failure required,
```

```
      otherwise error message generated (limcol):                              100
SLIP DIRECTIONS
Interval to search slip directions on each side of overall
 fall direction of potential failure, in degrees (degmax):                   0.000
Increment amount for slip direction, in degrees (deginc):                    0.000
Calculated number of slip directions tested for each lattice node:               1
SEARCH-LATTICE EXTENT AND RESOLUTION
VERTICAL EXTENT AND RESOLUTION
Minimum elevation of search-lattice nodes (m ) (zsmin):                   1000.000
Maximum elevation of search-lattice nodes (m ) (zsmax):                   9200.000
Search-lattice vertical spacing (m ) (zsrchres):                           100.000
Increment amount for potential failure surface sphere radius(m )(dr):      50.000
HORIZONTAL EXTENT AND RESOLUTION
Starting search-lattice horizontal node (ismin,jsmin):                      1    1
Ending search lattice horizontal node (ismax,jsmax):                       96   91
Horizontal spacing - multiple of DEM resolution (nsrchres):                      1
COARSE-TO-FINE SEARCH PARAMETERS
Horizontal and vertical multiplier for initial coarse search (multres):         8
Search iteration tolerance - percent change F (fostol):                     0.0100
------------
ADDITIONAL OUTPUT FILES AND PARAMETERS (see user manual for options)
isqout (search quality files):                                                   1
irelfos (relative F file):                                                       1
icritlattice (3D search lattice for critical nodes):                             1
ilattice (3D search lattice):                                                    1
isubsurf (3D subsurface factor of safety):                                       1
zfrac:                                                                       1.000
Create new DEM file (remove):                                                    M
   (surface with minimum F<foscut removed)
F cutoff for removing material from new DEM (foscut):                    5.000E+00

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
III. OUTPUT FILES GENERATED:

     LOCATION FOR OUTPUT FILES:
          R_sthel_output\

      R_sthel_out.txt
      R_sthel_errors_out.txt
      R_sthel_slope_out.asc
        Range: [    0.5858,   45.8266]
      R_sthel_fos3d_out.asc
        Range: [    2.2035,   18.5841]
      R_sthel_ordfos3d_out.asc
        Range: [    2.1205,   17.8549]
      R_sthel_fosvol_out.asc
        Range: [  1.0111E+08,  3.4992E+09]
      R_sthel_spheres_out.okc

     Optional files generated:
      R_sthel_fos3drel_out.asc
        Range: [    1.0000,    8.4339]
      R_sthel_newDEM_out.asc
        Range: [   743.2767,  2928.8840]

      R_sthel_numcols_out.asc

        Range: [   76, 1733]
      R_sthel_critcheck_out.asc
      R_sthel_boundcheck_out.asc
      R_sthel_subsurffos_out.txt
```

```
      R_sthel_critfoslattice_out.3D
      R_sthel_foslattice_out.3D
      R_sthel_ncolerr_out.txt
      R_sthel_searchgrid_out.asc

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
IV. RESULTS:
Number of trial surfaces tried:                                         521313
F < foscut found and newDEM_out file created?                              yes
Number of surfaces with active column totals less than limcol:             823
     Check file ncolerr_out for detailed information.
------------
3D POTENTIAL FAILURE - GLOBAL MINIMUM
Bishop's 3D factor of safety:                                           2.2035
Ordinary 3D factor of safety:                                           2.1205
Volume (m ^3):                                                     4.14604E+08
Horizontal surface area (m ^2):                                    2.30219E+06
Slip surface area (m ^2):                                          2.74618E+06
Weight (kg):                                                       9.95050E+09
Number of active columns:                                                  246
        x-center         y-center          z-center     radius
     563224.6317      5118596.1291        3900.0000   2.21644E+03
Slip direction, relative to search lattice:                            72.3351
End date and time: 07/11/2014  10:29:52
```

Figure 4.28. Text showing example of Scoops3D main output file. File from Mount St. Helens example R (file name: *R_sthel_out.txt*); see section 7.6.

4.5.1.2. Minimum Factor-of-Safety File

NAME: *<filein>_fos3d_out.asc*

FORMAT: ASCII raster

This output file contains the minimum 3D factor of safety calculated on the critical surface for each DEM cell by the user-specified limit-equilibrium method (Bishop's simplified or Ordinary). This file allows the user to view computed stability over the entire DEM area (fig. 4.29*A*). These results, an amalgamation of critical potential failure masses, can also be draped over topography (see fig. 1.2*A*). The file is written in ASCII raster format (see for example fig. 4.20). Some values in this file indicate lack of data or problems with the calculation of factor of safety for a specific DEM cell: (1) 9999.00 identifies cells not included in any trial surface computations, such as cells at the boundary of the DEM or with a NODATA (null) value in the DEM, (2) 111.00 indicates that the cells were contained only in trial slip surfaces with non-converging limit-equilibrium solutions or solutions were eliminated due to the user-specified filter (***absminma***, section 4.4.1.1.8), or (3) 100.0 indicates that the calculated factor of safety was greater than 100.0. Note that if the user-specified limit-equilibrium method is Bishop's simplified (***method*** = 'B' or 'b'), an additional file (*<filein>_ordfos3d_out.asc)* is created with the results from the Ordinary method for the same critical surfaces (see section 4.5.2.1).

4.5.1.3. Critical Size File

NAME: *<filein>_fosvol_out.asc* or *<filein>_fosarea_out.asc*

FORMAT: ASCII raster

Scoops3D generates one critical size file that depends on the primary size criteria selected by the user. If volume is the primary size criterion (***vacriterion*** = 'V' or 'v'), Scoops3D creates *<filein>_fosvol_out.asc*. If horizontal area is the primary size criterion (***vacriterion*** = 'A' or 'a'), Scoops3D creates *<filein>_fosarea_out.asc*. The critical size file is written in ASCII raster format (see for example fig. 4.20).

4.5.1.3.1. Critical Volumes File

The output file *<filein>_fosvol_out.asc* contains the volume associated with the critical surface for each DEM cell. An example of how this file can be used to create a map view is shown in figure 4.29*B*.

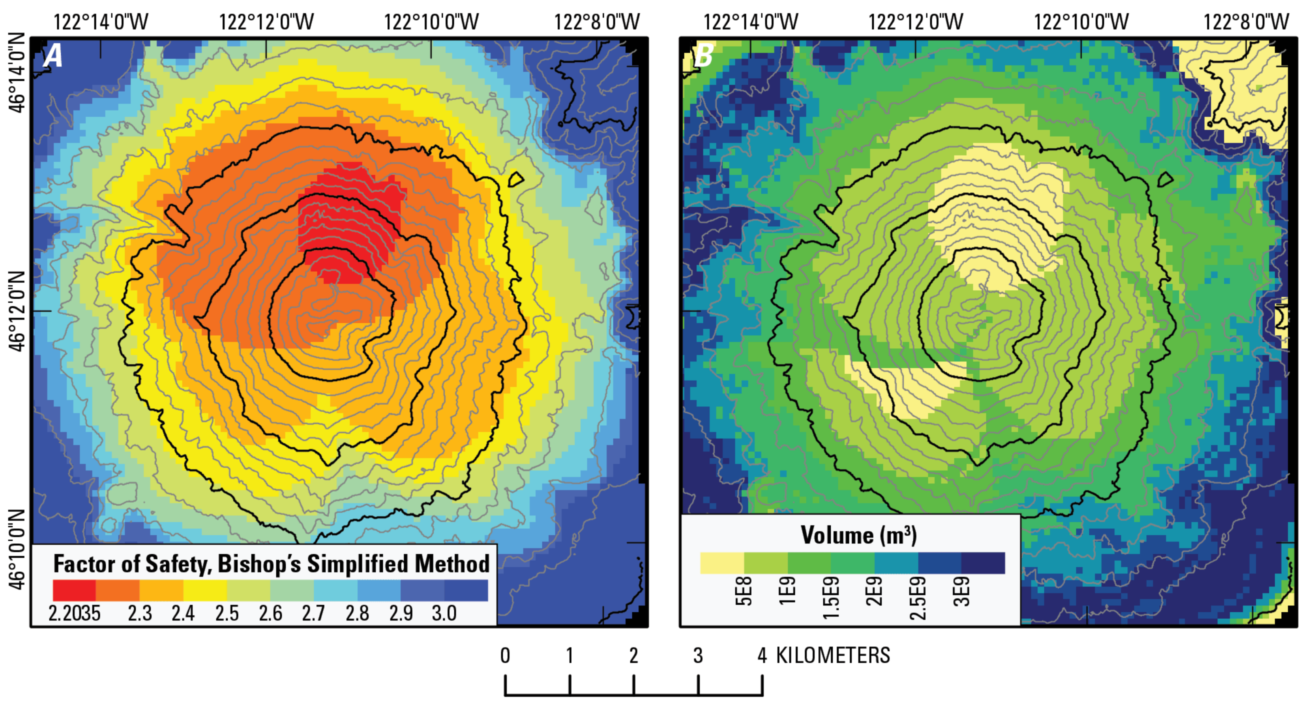


Figure 4.29. Examples of maps created from Scoops3D output files of minimum factor of safety and associated potential failure volumes. Maps created from Scoops3D Mount St. Helens example R output files (see section 7.6), with the addition of explanatory text and 100 m contours lines. *A*, Map of minimum factor of safety on the critical surfaces for each DEM cell calculated using Bishop's simplified method (derived from *R_sthel_fos3d_out.asc*). *B*, Map of potential failure volume associated with the critical surfaces shown in *A* (derived from *R_sthel_fosvol_out.asc*). Note that black cells on the boundaries were assigned the NODATA value of -9999, indicating that either there was no elevation value in the DEM at this cell or all trial surfaces that intersected this cell were truncated by the boundary of the DEM and therefore not analyzed. Maps created using Esri ArcMap software.

4.5.1.3.2. Critical Areas File

The output file *<filein>_fosarea_out.asc* contains the horizontal area associated with the critical surface for each DEM cell.

4.5.1.4. Critical-Trial-Surface File

NAME: *<filein>_spheres_out.okc*
FORMAT: text in XmdvTool (.okc) format

This output file lists additional data associated with the critical surface producing the minimum factor of safety for each DEM cell. The data contained in this file enable the user to reconstruct the single critical surface for a given DEM cell. The header of this file is in XmdvTool flat format, where the first line contains the number of variables and number of data points contained in the file and the number of variables multiplied by the number of data points (fig. 4.30). Subsequent header lines contain variable names, followed by lines containing the minimum and maximum values for each variable (in order of the variable names). See http://davis.wpi.edu/xmdv/fileformats.html for an explanation of the general XmdvTool (.okc) format. The variables contained in the file are:

- xcen, ycen, zcen – coordinates of the rotational center (critical node) of the critical surface in the coordinate system of the DEM,
- i and j – cell counter locations for each DEM cell,
- radius – radius of the sphere containing the critical surface,
- angle – azimuthal slip direction (counter-clockwise from the positive x-axis),
- cols – number of DEM cells (active columns) intersected by the critical surface,
- vol – volume of the critical potential failure mass,
- area – horizontal surface area of the critical potential failure mass,
- F_Bish – factor of safety computed using Bishop's simplified method (only listed if ***method*** = 'B' or 'b'), and
- F_Ord – factor of safety computed using the Ordinary method.

Note that if Bishop's simplified method was specified, the Ordinary *F* values are for the same critical surfaces identified with Bishop's method. If the Ordinary method was specified, the Ordinary *F* values are for the critical surfaces identified by the Ordinary method (which may differ from those found by Bishop's simplified method). If length units have been defined by the user in the main parameter input file, the variable names listed in the header include the character '_' followed by length units for the appropriate variables. If the same critical surface defines the minimum factor of safety for multiple DEM cells, the file lists the same information for each DEM cell affected by that critical surface.

```
  12 8633 103596
xcen_m
ycen_m
zcen_m
i
j
radius_m
angle
cols
vol_m^3
area_m^2
F_Bish
F_Ord
  558424.631687000 567124.631687000 4
  5111796.12910190 5120496.12910190 4
  1100.00 9200.00 4
  1 96 4
  1 91 4
  515.734 8229.85 4
  3.273308E-02 359.773 4
  76 1733 4
  1.011122E+08 3.499162E+09 4
  676022. 1.683488E+07 4
  2.20350 18.5841 4
  2.07652 17.2802 4
558624.6317 5111896.1291 3300.0000 6 1 2.392E+03 235.10  192 1.039E+08 1.793E+06
6.3586  6.1692
558824.6317 5112096.1291 2100.0000 7 1 1.319E+03 234.29  213 2.912E+08 2.003E+06
5.7446  5.1016
558924.6317 5112096.1291 2300.0000 8 1 1.484E+03 235.97  223 2.860E+08 2.089E+06
5.5059  5.0179
558924.6317 5112096.1291 2300.0000 9 1 1.484E+03 235.97  223 2.860E+08 2.089E+06
5.5059  5.0179
558924.6317 5112096.1291 2300.0000 10 1 1.484E+03 235.97  223 2.860E+08 2.089E+06
5.5059  5.0179
558924.6317 5112096.1291 2300.0000 11 1 1.484E+03 235.97  223 2.860E+08 2.089E+06
5.5059  5.0179
558924.6317 5112096.1291 2300.0000 12 1 1.484E+03 235.97  223 2.860E+08 2.089E+06
5.5059  5.0179
558924.6317 5112096.1291 2300.0000 13 1 1.484E+03 ...
```

Figure 4.30. Text excerpt from an example critical-trial-surface output file. File from Mount St. Helens example R (file name: *R_sthel_spheres_out.okc)*; see section 7.6. The header lines are in the XmdvTool format. In this example, ***lengthunits*** = 'm' was specified by the user in the main parameter input file. The first line contains the number of variables, data points, and the product of the two. Lines 2 through 13 list the variable names, and lines 14 through 25 list the minimum and maximum values for each variable (the value 4 in each line can be ignored). Subsequent lines contain values for each variable at each data point.

4.5.1.5. Slope File

NAME: *<filein>_slope_out.asc*

FORMAT: ASCII raster

This output file contains the ground-surface slope, in degrees, computed by Scoops3D for each DEM cell. The slope file is a grid written in ASCII raster format (see for example fig. 4.20).

Slope for each cell is computed using the elevations of the surrounding eight cells (Horn, 1981; Burrough and McDonnell, 1998). To compute slope (converted from radians to degrees) for a DEM cell of interest (center cell 'e' in fig. 4.31), Scoops3D uses the formula:

$$slope = \left[\arctan \sqrt{(dz/dx)^2 + (dz/dy)^2} \right] (180/\pi)\,, \qquad (4.5)$$

where the rate of elevation change in the x direction, *dz/dx* for the center is:

$$dz/dx = ((c + 2f + i) - (a + 2d + g) / (8 * \text{cellsize}), \qquad (4.6)$$

and the rate of elevation change in the y direction, *dz/dy* is:

$$dz/dy = ((g + 2h + i) - (a + 2b + c)) / (8 * \text{cellsize}). \qquad (4.7)$$

Here, the letters denote elevations in the cells surrounding the center cell of interest (fig. 4.31) and cellsize is the length of the DEM cell as specified in the header of the DEM file.

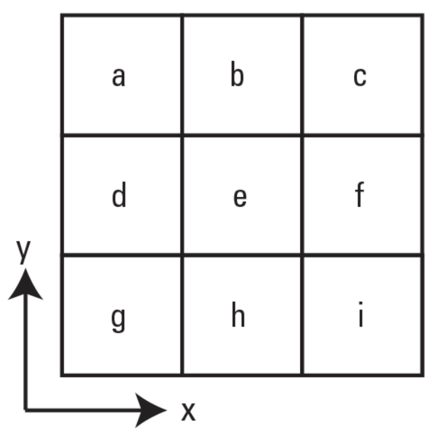


Figure 4.31. Schematic diagram showing plan view of cell identification letters used for computing ground-surface slope. Cell letters are used in equations 4.6 and 4.7.

4.5.1.6. Error File

NAME: *<filein>_errors_out.txt*
FORMAT: text

An error file is always created during a Scoops3D run, but may be empty if there are no errors related to input files. This file lists errors associated with the main parameter input file, header problems with the input files, non-existent files, or inconsistencies between files. Some input file problems cause Scoops3D to stop execution, whereas minor errors do not stop execution but are reported in the error file. If this file lists any errors, the user should modify the input files as needed or carefully check the files to assure correct interpretation by Scoops3D.

4.5.2. Conditional Output Files

During the execution of a Scoops3D run, some additional files may be generated depending on analysis criteria or problems encountered during the run. The conditions for creation of each of these additional files are listed with each file description and in table 4.4. This is in contrast to optional output files, which are explicitly requested by the user (section 4.5.3). For example, Scoops3D creates some of the conditional files when specific parameters or combinations of parameters are set (for example, if ***srch*** = ‘single’ and ***method*** = ‘O’ or ‘o’, then the file *<filein>_foslocal_out.txt* is created). Other files described in this section provide information about trial surfaces that did not meet user-specified criteria, such as the minimum number of active columns within a potential failure mass, or trial surfaces that were eliminated due to filtering constraints. Note that Scoops3D execution does not halt if these conditions occur. These files can be used to ascertain whether the overall solutions are acceptable for the user’s purposes.

4.5.2.1. Minimum Factor-of-Safety File – Ordinary (Fellenius) Method

CONDITIONS FOR FILE CREATION: Stability analysis method is Bishop; ***method*** = ‘B’ or ‘b’
NAME: *<filein>_ordfos3d_out.asc*
FORMAT: ASCII raster

This output file contains the minimum 3D factor of safety calculated for the critical surface affecting each DEM cell using the Ordinary (Fellenius) method, and is created as a supplemental file when the user selects Bishop’s simplified method. This additional file allows the user to compare slope stability computed using the Ordinary method with results using the Bishop’s simplified method for the same ***critical trial surfaces***, as determined using Bishop’s method. Note that these may not be the Ordinary method critical surfaces – the user should run Scoops3D with the Ordinary option selected to obtain these values. The file is written in ASCII raster format (see for example fig. 4.20). Some values in this file indicate lack of data or problems with the calculation of factor of safety for a specific DEM cell: (1) 9999.00 identifies cells at the boundary of the DEM or with a NODATA value in the DEM and (2) 100.0 indicates that the calculated factor of safety was greater than or equal to 100.0.

4.5.2.2. Column Warning File

CONDITIONS FOR FILE CREATION: existence of potential failure masses containing fewer active columns than the value of ***limcol***

NAME: *<filein>_ncolerr_out.txt*

FORMAT: text

This output file is created only if the number of active columns in a potential failure mass falls below the user-specified limit, ***limcol*** (section 4.4.1.1.10). This condition does not terminate Scoops3D execution, but the factor of safety, volume, and area computations for this potential failure mass may be suspect. This file contains a listing of all surfaces within the user-specified size constraints but with a potential failure mass containing a number of active columns less than ***limcol***. It lists all trial surfaces failing this column criterion, not just the critical surfaces. To examine the number of active columns defining only the critical surfaces, the user should view the contents of the *<filein>_numcols_out.asc* file (generated when ***isqout*** = 1, section 4.5.3.2.2). If many trial surfaces are flagged as having too few active columns, the user may wish to either increase the resolution of the DEM grid (effectively creating more columns) so that more columns are intersected by trial surfaces (section 5.3.4).

The column warning file contains two header lines and then a series of lines for each trial surface not meeting the user-selected ***limcol*** criteria; an example is shown in figure 4.32. This information includes:

- # cols – number of DEM cells (active columns) in the potential failure mass,
- xcen, ycen, zcen – coordinates of the rotational center of the trial surface specified in the coordinate system of the DEM,
- radius - radius of the sphere containing the trial surface,
- volume **-** computed volume of the potential failure mass,
- area - horizontal area of the potential failure mass, and either
- F_Bish – computed factor of safety using Bishop’s simplified method (if ***method*** = ‘B’ or ‘b’), or F_Ord – computed factor of safety using the Ordinary (Fellenius) method (if ***method*** = ‘O’ or ‘o’).

```
Trial surfaces with columns < limcol
#cols xcen_m  ycen_m  zcen_m  radius_m volume_m^3 area_m^2 F_Bish
92 561224.6317 5112296.1291 1800.000 740.161 1.053E+08 8.366E+05 6.6959
83 562024.6317 5112296.1291 1800.000 663.685 1.062E+08 7.556E+05 6.6515
87 562824.6317 5112296.1291 1800.000 694.758 1.056E+08 8.033E+05 5.5904
95 564424.6317 5112296.1291 1800.000 771.473 1.014E+08 8.524E+05 7.3548
91 558824.6317 5113096.1291 1800.000 795.604 1.073E+08 8.183E+05 4.1298
95 559624.6317 5113096.1291 1800.000 702.510 1.068E+08 8.171E+05 7.0428
...
```

Figure 4.32. Text excerpt from a column warning output file. File from Mount St. Helens example R (file name: *R_sthel_ncolerr_out.txt*); see section 7.6.

4.5.2.3. Filtered Surfaces File

CONDITIONS FOR FILE CREATION: ***method*** = 'B' or 'b' and either convergence problems or $|m_\alpha|$ > ***absminma***

NAME: *<filein>_filter_out.txt*
FORMAT: text

This output file lists details associated with all trial surfaces (meeting the user-specified size constraints) that were either filtered or failed to converge during factor-of-safety, *F*, iterations. This file is created when at least one trial surface meets one of these conditions—such conditions do not terminate a Scoops3D run, but do indicate that Scoops3D was unable to calculate a factor of safety for some potential failure masses. The factor of safety is assigned a value of 111.0 if a solution cannot be reached in 25 iterations (if monotonically converging). We have found that most solutions converge in 4 to 5 iterations (section 2.3.2). The user-specified filtering option (***absminma*** – see section 4.4.1.1.8) and non-convergence problems occur only when using Bishop's simplified method. The factor of safety for trial surfaces that converge but do not meet the filter criteria are also shown in this file. Note, however, that these surfaces are not included in the analysis of critical surfaces (and therefore are not included in files such as the factor-of-safety file, *<filein>_fos3d_out.asc*).

The filtered surfaces file contains several header lines and then lists the following values for each filtered surface:

- xcen, ycen, zcen – coordinates of the rotational center of the trial surface, in the coordinate system of the DEM,
- radius - radius of the sphere containing the trial surface,
- angle - slip direction in degrees (counter-clockwise from the positive x-axis),
- minma – minimum value of m_α computed with Bishop's simplified method for the potential failure mass,

- F_Bish - factor of safety computed using Bishop's simplified method (if ***method*** = 'B' or 'b'), and
- F_Ord - factor of safety computed using the Ordinary (Fellenius) method.

An example of *<filein>_filter_out.txt* is shown in figure 4.33.

```
This file contains data for trial slip surfaces filtered by absminma
 and nonconverging surfaces.
These data are not used in the search for minimum F values.
xcen_ft    ycen_ft  zcen_ft radius_ft angle minma  F_Bish F_Ord
1258401.9727 216371.9230 200.000 51.234 120.068 9.473E-03 111.000 1.220
1258401.9727 216371.9230 200.000 51.234 122.068 6.661E-03 111.000 1.220
1258401.9727 216371.9230 200.000 51.234 124.068 4.574E-03 111.000 1.220
1258401.9727 216421.9230 200.000 54.561  16.907 3.391E-02 111.000 1.002
```

Figure 4.33. Text excerpt from a filtered surfaces output file. File from a variation of Seattle example Q (file name: *Q_seawet_filter_out.txt*); see section 7.5. Note that, in this example, no m_α filter was specified by the user (***absminma*** = 0), so all surfaces listed here failed to converge within 25 iterations.

4.5.2.4. Filtered Surfaces Location File

CONDITIONS FOR FILE CREATION: ***method*** = 'B' or 'b' and either convergence problems occurred or $|m_\alpha|$ > ***absminma***

NAME: *<filein>_filtergrid_out.asc*

FORMAT: ASCII raster

This raster grid output file contains the number of times that each DEM cell was intersected by trial surfaces that were filtered out or failed to converge. This file is created only when Bishop's simplified method is selected and at least one trial surface was filtered or failed to converge during factor-of-safety iterations (section 4.5.2.3). This file is useful for viewing whether excessive factor-of-safety computational problems were encountered in areas of interest within the DEM (see fig. 5.11). The file is written in ASCII raster format (see for example fig. 4.20).

4.5.2.5. Detailed Forces and Factor-of-Safety File

CONDITIONS FOR FILE CREATION: ***method*** = 'O' or 'o' and ***srch*** = 'single'

NAME: *<filein>_foslocal_out.txt*

FORMAT: text

This output file is automatically generated only if the user specifies the Ordinary (Fellenius) method with a single trial surface analysis. The file contains information about the local factor of safety (resisting/driving forces) at the base of each column intersected by the user-specified trial surface. This information can be used to carefully examine individual column driving and resisting forces acting on a specific trial surface. This file is available only with the Ordinary method because this method does not consider the entire mass during the solution of *F*.

The detailed forces file contains one header line followed by lines containing:

- i, j - cell counter (section 4.4.1.1.9.1) indicating the horizontal location of the column,
- sliparea – trial surface area,
- res. frict - frictional component of the resisting force acting on the column base,
- res. coh. - cohesive component of the resisting force acting on the column base,
- total res. - total resisting force on the column,
- total driv. - total driving force on the column, and
- res./driv. – ratio of total resisting/total driving force for the column (the local factor of safety).

Note that the local factor of safety can be negative because the driving force on the base of a single column may be in a direction opposite that of the overall slip direction. An example of this file is shown in figure 4.34.

```
i  j sliparea res. frict. res. coh. total res. total driv. res./driv.
42 25 4.3506E-02 4.2096E-03 1.3052E-01 3.5011E+00 1.5124E-01 2.3150E+01
43 25 6.9415E-02 1.0085E-02 2.0824E-01 5.6714E+00 3.8340E-01 1.4792E+01
44 25 8.0718E-02 1.3279E-02 2.4215E-01 6.6342E+00 5.3335E-01 1.2439E+01
45 25 7.7021E-02 1.1843E-02 2.3106E-01 6.3092E+00 5.0176E-01 1.2574E+01
46 25 5.7797E-02 6.6172E-03 1.7339E-01 4.6769E+00 2.9536E-01 1.5835E+01
47 25 2.2377E-02 1.2505E-03 6.7131E-02 1.7776E+00 5.8735E-02 3.0265E+01
38 26 9.0524E-02 1.9834E-02 2.7157E-01 7.6369E+00 5.5311E-01 1.3807E+01
39 26 1.7547E-01 6.8817E-02 5.2642E-01 1.5579E+01 2.0496E+00 7.6011E+00
...
```

Figure 4.34. Text excerpt from a detailed forces output file. File from example G using Ordinary method (file name: *G_emb10single_foslocal_out.txt*); see section 7.3.

4.5.2.6. Removed Failure Masses File

CONDITIONS FOR FILE CREATION: ***remove*** = ‘A’ or ‘a’ and calculation of potential failure masses with *F* < ***foscut***

NAME: *<filein>_spheresltcut_out.txt*

FORMAT: text

If the user chooses to create a new DEM with all potential failure masses removed (***remove*** = ‘A’ or ‘a’) having a factor of safety, *F*, less than the value of ***foscut*** (section 4.4.1.1.11.1), this output file lists additional information about the masses removed from the original DEM. This file can be used to recreate any trial surfaces that were removed. The text file contains two header lines (fig. 4.35). For an explanation of the variables contained in this file, see the variables described for the critical-trial-surfaces output file, *<filein>_spheres_out.okc* (section 4.5.1.4).

```
Potential failure masses with F < 1.400
xcen_ft    ycen_ft  zcen_ft radius_ft angle volume_ft^3 area_ft^2 F_Bish
1254251.9727 217221.9230 650.00 552.6975 142.9037 2.249E+05 1.835E+04 1.3719
1254451.9727 217221.9230 450.00 310.1039 135.4226 3.314E+05 2.168E+04 1.3355
1255451.9727 219021.9230 250.00 241.0051 145.4801 1.063E+05 8.536E+03 1.3565
1258251.9727 219021.9230 450.00 380.7452 23.6471 9.661E+05 5.019E+04 1.3483
1255651.9727 219221.9230 250.00 224.5933 143.7098 2.904E+05 1.711E+04 1.2876
1255651.9727 219221.9230 250.00 234.5933 143.0667 6.185E+05 3.362E+04 1.3433
1258151.9727 215921.9230 450.00 207.5477 23.3521 1.164E+05 1.072E+04 1.3880
1258151.9727 216021.9230 350.00 116.7330 335.9197 1.106E+05 8.740E+03 1.3817
1254051.9727 216421.9230 350.00 183.2500 151.8632 1.144E+05 9.193E+03 1.3256
...
```

Figure 4.35. Text excerpt from a removed failure masses output file. File from example P (file name: *P_seadry _spheresltcut_out.txt*); see section 7.5.

4.5.3. Optional Output Files

Scoops3D can generate a variety of optional output files useful for analyzing certain stability scenarios. The user can select any or all of these files by setting flags in the main parameter input file or by using Scoops3D-i (see section 4.3.3.6). Caution should be exercised when selecting optional 3D output files – they can occupy considerable storage space.

4.5.3.1. New DEM File

SELECTION OPTION: ***remove*** = ‘A’, ‘a’, ‘L’, ‘l’, ‘M’, or ‘m’

NAME: *<filein>_newDEM_out.asc*

FORMAT: ASCII raster

This optional output file contains a new DEM with user-specified potential failure masses removed from the original DEM, creating a new ground surface coincident with the trial surfaces of these specified potential failure masses. Parts of the DEM not affected by the potential failure masses remain the same. This file is created only if the ***remove*** parameter (section 4.4.1.1.11.1) in the main parameter input file is ‘A’, ‘L’, or ‘M’ (or the lower case equivalents). If the parameter equals ‘N’ or ‘n’ or the parameter line pair is absent from the main input file, then the file is not created. A value of ‘A’ or ‘a’ removes all potential failures with factors of safety less than a cutoff value (***foscut***) from the DEM. ‘L’ or ‘l’ removes only the largest potential failure mass with a factor of safety less than the cutoff value. ‘M’ or ‘m’ removes the failure mass with the minimum global factor of safety. If no critical potential failure masses have a factor of safety less than the cutoff, this output file is not generated. The file is written in ASCII raster format (see for example fig. 4.20).

4.5.3.2. Search Quality Files

SELECTION OPTION: ***isqout*** = 1

If this option is selected (***isqout*** = 1), Scoops3D generates three or four (four if ***srch*** = ‘box’ is also selected) additional output files. These files can be used to check the overall quality of both the factor of safety solutions and the search. Typically, this option is used early in an analysis process and then unselected after the user is satisfied with the overall solution and search quality (see section 5.1).

4.5.3.2.1. Critical-Size Check File

NAME: *<filein>_critcheck_out.asc*
FORMAT: ASCII raster

This output file contains a raster grid that indicates whether the size of the critical potential failure determined at each DEM cell was close to the upper or lower size limit, based on the user-specified primary criterion of either volume or area and associated tolerances. A user may view this file to determine whether the factor-of-safety search has been overly limited by size restrictions (see section 5.3.2; fig. 5.3). To find the global minimum factor of safety, trial surfaces should not be restricted by size limits, although limitations may be acceptable if the user is only interested in a specific size range. Each cell with a valid computed factor of safety can have one of four values (table 4.5). The file is written in ASCII raster format (see for example fig. 4.20).

Table 4.5 List of numeric codes used in the critical-size check output file *(<filein>_critcheck_out.asc)*.

[Scoops3D assigns the numeric code by comparing the size of the critical potential failure mass for each DEM cell with the user-specified primary size criterion]

Code	Explanation	
	Volume is primary criterion (***vacriterion*** = 'V' or 'v')	Area is primary criterion (***vacriterion*** = 'A' or 'a')
-1	DEM cell was not included in any trial surface	DEM cell was not included in any trial surface
0	Size was not restricted	Size was not restricted
1	Volume was less than ***vmin***+***tol***,	Horizontal area was less than ***armin***+***tol***,
2	Volume was greater than ***vmax-tol***	Horizontal area was greater than ***armax-tol***

4.5.3.2.2. Number of Columns File

NAME: *<filein>_numcols_out.asc*

FORMAT: ASCII raster

This output file contains a raster grid showing the number of active columns associated with the critical potential failure mass for each DEM cell. A user can view the contents of this file to determine whether all regions of interest have sufficient columns in the critical potential failure masses (see section 5.3.4; fig. 5.5) to ensure accurate factor of safety, volume, and area calculations. The file is written in ASCII raster format (see for example fig. 4.20).

4.5.3.2.3. Horizontal Search Space File

NAME: *<filein>_searchgrid_out.asc*

FORMAT: ASCII raster

This output file contains a raster grid showing the location of DEM cells above which search-lattice nodes are located. Thus, this file shows the horizontal alignment of the search space relative to the DEM grid as well as the horizontal search-lattice spacing. Visualization of this file can help the user assure the proper alignment of the horizontal search space in relation to the DEM (fig. 4.36), and may be particularly helpful when using a search grid file (section 4.4.2.1.3). Note that the boundaries of the search grid file may be larger than the boundary of the DEM (fig. 4.36), or may be restricted to a region smaller than the DEM. This file is generated as a union of the user-input search area (from either a search file or a box) and the DEM area. Each grid cell contains one of four possible numbers (table 4.6). The file is written in ASCII raster format (see for example fig. 4.20).

Table 4.6 List of numeric codes used in the horizontal search space output file (*<filein>_searchgrid_out.asc*).

[Numeric codes indicate how the horizontal extent of the 3D search lattice overlaps with the DEM. Cells with negative numbers indicate that search-lattice nodes do not exist at that horizontal location]

Code	Explanation	
	Search-lattice nodes exist at location	Location is inside the boundary of the DEM
-1	No	Yes
-11	No	No
2	Yes	Yes
22	Yes	No

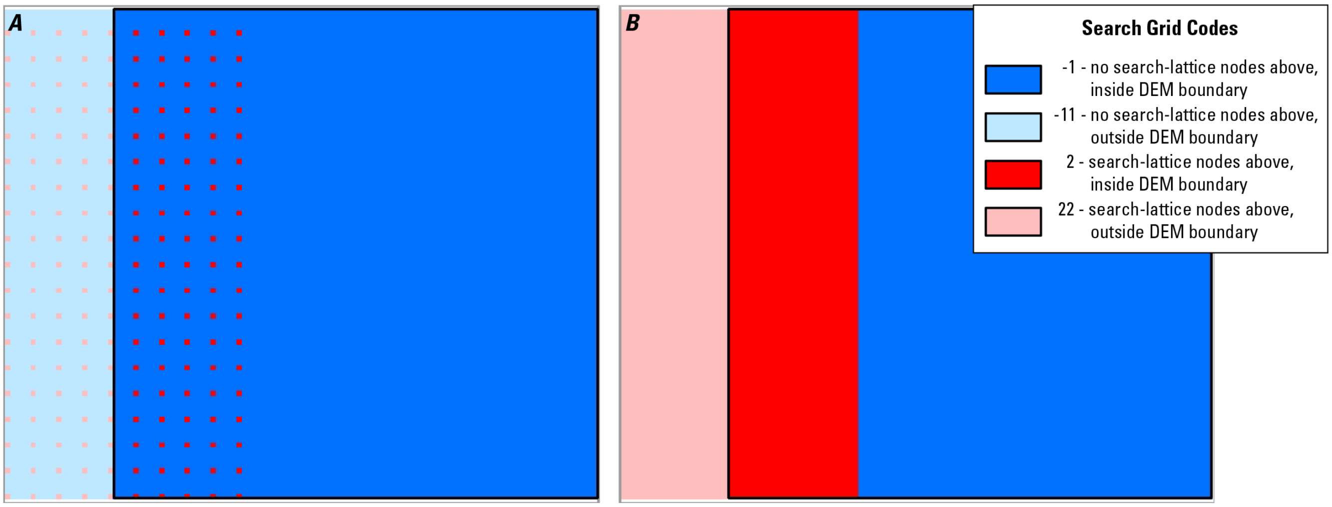


Figure 4.36. Examples of maps created from Scoops3D output files illustrating the horizontal extent of the search lattice relative to the DEM. Data portrayed are contained in horizontal search space output files (*<filein>_searchgrid_out.asc*) and show two search lattices that extend outside the boundary of the DEM. Black box outline indicates the boundary of the DEM. Red indicates DEM cells above which there are some search-lattice nodes. Blue indicates DEM cells above which there are no search-lattice nodes. *A*, Search lattice with a horizontal multiplier of 5 (***nsrchres*** = 5). *B*, Search lattice with a horizontal multiplier of 1 (***nsrchres*** = 1). Maps created using Esri ArcMap software.

4.5.3.2.4. Search-Lattice Boundary Check File

SELECTION OPTION: ***isqout*** = 1 and ***srch*** = 'box'

NAME: *<filein>_boundcheck_out.asc*

FORMAT: ASCII raster

This output file contains a raster grid identifying the DEM cells where a search-lattice node associated with a critical surface (here called a ***critical node***) is located on a boundary of the search lattice. A user could view this file to determine whether the search lattice is too restrictive to ensure finding critical surfaces with the minimum *F* (see section 5.3.5; fig. 5.8). In this file, areas of interest in the DEM should contain the value zero. Non-zero values indicate that the extent of the search lattice was most likely not sufficient to locate the critical surface at the specified DEM cell. If a critical node is located on multiple boundaries of the search lattice, the value assigned to the lattice boundary check array is the sum of the values in table 4.7. For example, a DEM cell with a critical search-lattice node location on the uppermost (highest elevation), western boundary of the search lattice would be assigned a value 9+100 = 109. The file is written in ASCII raster format (see for example fig. 4.20). An example map created from this file is shown in figure 4.37.

Table 4.7. List of numeric codes used in the search-lattice boundary check file (*<filein>_boundcheck_out.asc*).

[Note that if the search lattice is restricted on more than one boundary, the value assigned to the boundary check array by Scoops3D will be the sum of the values in this table]

Code	Problem	Explanation
0	---	Critical node not on boundary, search lattice was not restricted
100	***ismin*** is too large	Critical node on west side of search lattice
900	***ismax*** is too small	Critical node on east side of search lattice
10	***jsmin*** is too large	Critical node on south side of search lattice
90	***jsmax*** is too small	Critical node on north side of search lattice
1	***zsmin*** is too large	Critical node on the bottom of the search lattice
9	***zsmax*** is too small	Critical node on the top of the search lattice
-9999	---	No trial surfaces found

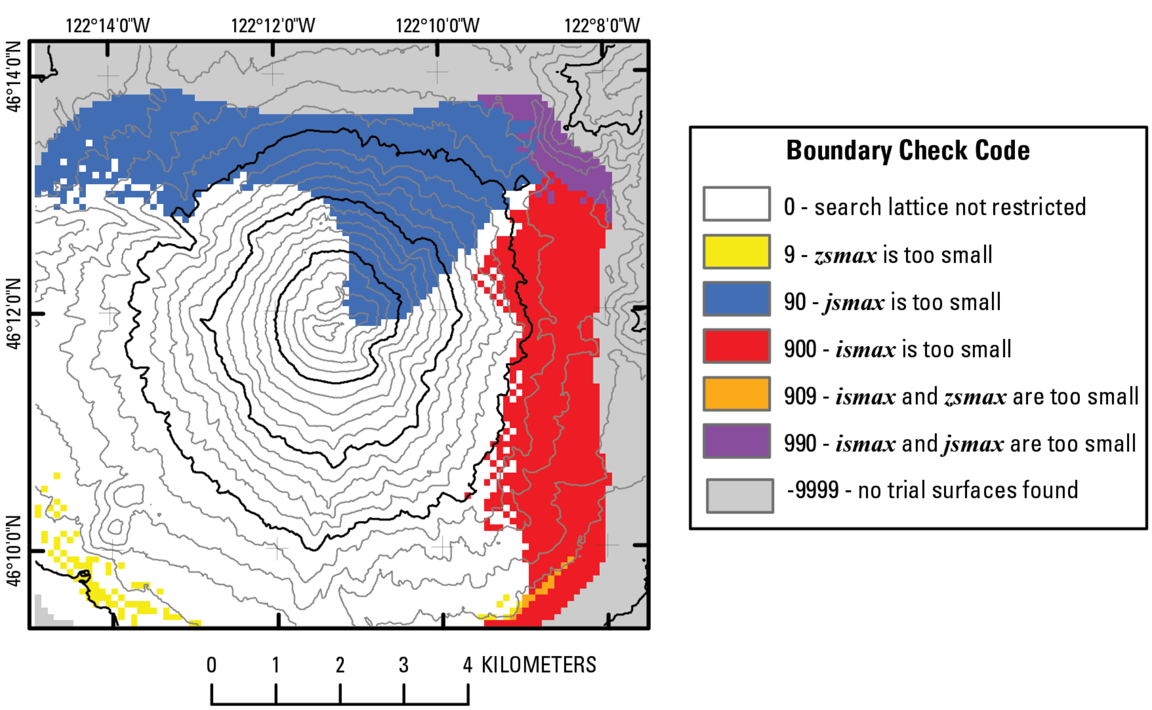


Figure 4.37. Example of a map created from a search-lattice boundary check file (*<filein>_boundcheck_out.asc*) for a search that was limited on the north and east sides of the DEM. Numeric codes are explained in table 4.7. The 100 m contour lines are derived from the DEM for Scoops3D Mount St. Helens example R (file name: *sthel_res100mDEM.asc*); see section 7.6. Map created using Esri ArcMap software.

4.5.3.3. Relative-Minimum Factor-of-Safety File

NAME: *filein>_fos3drel_out.asc*
FORMAT: ASCII raster

This output file contains a raster grid of the relative-minimum 3D factors of safety calculated for each DEM cell by the user-selected limit-equilibrium method (Bishop's or Ordinary). Relative factor of safety is defined as the computed minimum factor of safety at a DEM cell divided by the global minimum factor of safety. These normalized values can provide a convenient way to compare the locations of unstable areas between different scenarios. Invalid factor-of-safety results are reported in the same manner as in the minimum factor of safety file described in section 4.5.1.2. The file is written in ASCII raster format (see for example fig. 4.20).

4.5.3.4. 3D Search-Lattice Files

Scoops3D has two options for creating 3D files containing results from the search lattice located above the DEM. One option (***icritlattice***) creates a file containing *F* values for search nodes associated with critical surfaces affecting the DEM (section 3.2). The other option (***ilattice***) creates a file containing the minimum *F* values found at each lattice node. Both search-lattice files contain the x, y, and z coordinates and an associated factor of safety found at each node in the 3D search lattice.

3D visualization of the 3D search-lattice file highlighting the critical nodes (*<filein>_critfoslattice_out.3D*) can help the user decide if the limits of the search lattice are adequate (fig. 4.38 and section 5.3.5); a well-defined search-lattice space ensures that the minimum *F* is found for all cells in the DEM. On the other hand, 3D visualization of the 3D search-lattice file containing the minimum *F* values for all the search nodes *(<filein>_foslattice_out.3D*) may be used to examine the overall spatial pattern of the lowest factors of safety found, but may not be as helpful for deciding the limits of the search lattice because not all of the factors of safety in the file are associated with a critical surface affecting the DEM. The pattern in this file (*<filein>_foslattice_out.3D*) is similar in appearance to the results of a grid search for the global minimum in other slope-stability software (for example Krahn, 2004; O. Hungr Geotechnical Research Inc., 2010).

4.5.3.4.1. 3D Search-Lattice File Highlighting Critical Nodes

SELECTION OPTION: ***icritlattice*** = 1

NAME: *<filein>_critfoslattice_out.3D*

FORMAT: text in Point3D format

This 3D optional output file of the search lattice highlighting critical nodes is generated when ***icritlattice*** = 1. Followed by a simple header in Point3D format (see example in fig. 4.38), each line in the 3D file contains the x, y, z coordinates of the lattice node in the coordinate system of the DEM, and the minimum factor of safety found for critical surfaces centered at that node. If multiple critical surfaces used the same lattice node, then only the minimum of the multiple *F* values is contained in the file. All search nodes that did not generate a critical surface are assigned the value 10000.0000. If a search-lattice node did not yield any valid trial surfaces, one of three values is assigned: (1) 9999.00 indicates no valid potential failure masses could be found within the specified size range, (2) 111.00 indicates all trial surfaces had non-converging limit-equilibrium solutions or solutions eliminated due to user-defined m_α filter (section 4.4.1.1.8), and (3) 100.00 indicates that all trial surfaces had a calculated factor of safety greater than or equal to 100.0. A 3D visualization of an example 3D search-lattice file highlighting the critical nodes is shown in figure 4.39.

```
x_m y_m z_m F_Bish
558024.6317     5111496.1291     1000.0000 9999.0000
558024.6317     5111496.1291     1800.0000 9999.0000
558024.6317     5111496.1291     2600.0000 9999.0000
558024.6317     5111496.1291     3400.0000 9999.0000
558024.6317     5111496.1291     4200.0000 9999.0000
558024.6317     5111496.1291     5000.0000 9999.0000
558024.6317     5111496.1291     5800.0000 9999.0000
558024.6317     5111496.1291     6600.0000 9999.0000
558024.6317     5111496.1291     7400.0000 9999.0000
558024.6317     5111496.1291     8200.0000 9999.0000
558024.6317     5111496.1291     9000.0000 9999.0000
558824.6317     5111496.1291     1000.0000 9999.0000
558824.6317     5111496.1291     1800.0000 9999.0000
558824.6317     5111496.1291     2600.0000 9999.0000
558824.6317     5111496.1291     3400.0000 9999.0000
558824.6317     5111496.1291     4200.0000 9999.0000
558824.6317     5111496.1291     5000.0000 9999.0000
558824.6317     5111496.1291     5800.0000 9999.0000
558824.6317     5111496.1291     6600.0000 9999.0000
558824.6317     5111496.1291     7400.0000 10000.0000
558824.6317     5111496.1291     8200.0000 10000.0000
558824.6317     5111496.1291     9000.0000 10000.0000
...
563024.6317     5118696.1291     4200.0000 10000.0000
563024.6317     5118696.1291     4400.0000 10000.0000
563224.6317     5118696.1291     3600.0000 10000.0000
563224.6317     5118696.1291     4000.0000   2.2046
563224.6317     5118696.1291     4400.0000 10000.0000
563424.6317     5118696.1291     3600.0000 10000.0000
563424.6317     5118696.1291     3800.0000 10000.0000
563424.6317     5118696.1291     4000.0000   2.2225
563424.6317     5118696.1291     4200.0000 10000.0000
563424.6317     5118696.1291     4400.0000 10000.0000
563424.6317     5118696.1291     4600.0000 10000.0000
563424.6317     5118696.1291     4800.0000 10000.0000
563624.6317     5118696.1291     4400.0000   2.2605
563624.6317     5118696.1291     4800.0000 10000.0000
563824.6317     5118696.1291     4400.0000   2.2907
563824.6317     5118696.1291     4600.0000   2.2767
563824.6317     5118696.1291     4800.0000   2.2758
563824.6317     5118696.1291     5000.0000 10000.0000
563824.6317     5118696.1291     5200.0000 10000.0000
564024.6317     5118696.1291     4400.0000 10000.0000
564024.6317     5118696.1291     4800.0000   2.3077
564024.6317     5118696.1291     5200.0000 10000.0000
564224.6317     5118696.1291     4400.0000 10000.0000
564224.6317     5118696.1291     4600.0000 10000.0000
564224.6317     5118696.1291     4800.0000   2.3728
564224.6317     5118696.1291     5000.0000   2.3525
564224.6317     5118696.1291     5200.0000 10000.0000
564224.6317     5118696.1291     5400.0000 10000.0000

...
```

Figure 4.38. Text excerpts from a 3D search-lattice output file highlighting the critical nodes. File from the Mount St. Helens example R displayed in figure 4.39 (file name: *R_sthel_critfoslattice_out.3D*). Note that some nodes contained in this excerpt had either no valid trial surfaces (values of 9999.0000) or only trial surfaces associated with non-critical surfaces (values of 10000.0000).

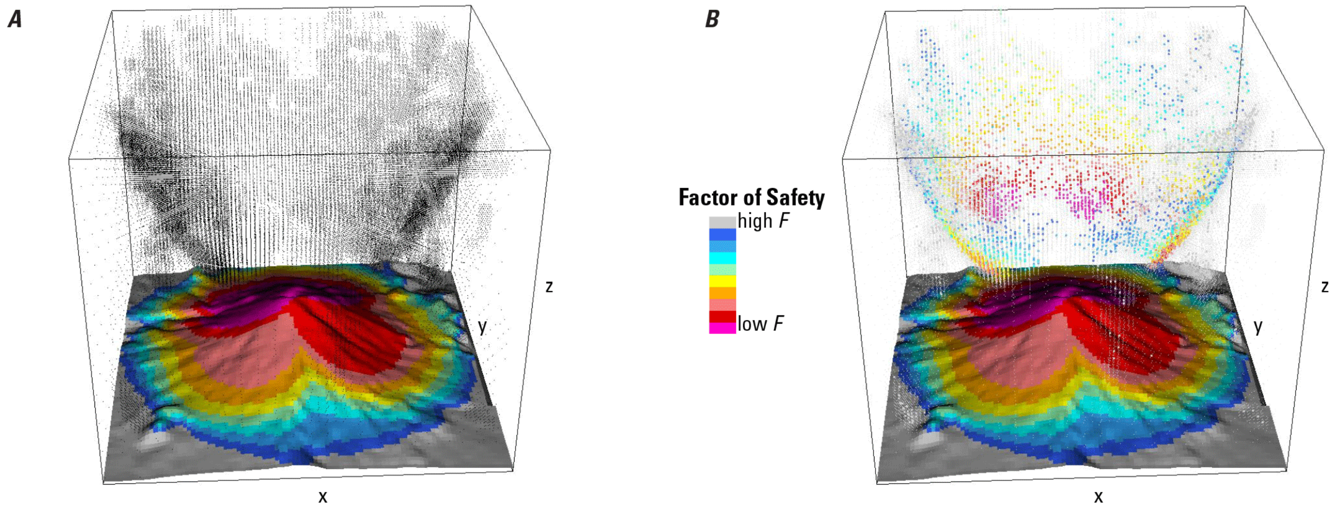


Figure 4.39. Images showing the 3D visualization of the search lattice highlighting critical nodes displayed above the corresponding factor-of-safety map draped on topography. Files from the Mount St. Helens example R (file names: *R_sthel_critfoslattice_out.3D* and *R_sthel_fos3d_out.asc*); see section 7.6. The example uses a coarse-to-fine search. *A*, All searched lattice nodes are shown with small black points. *B*, Search-lattice nodes with a critical surface are shown with colors assigned to factor of safety (*F*); high values of *F* and nodes that are not associated with critical surfaces are shown in grey. Note that each critical node in the lattice is associated with a critical surface in the factor-of-safety map. Images produced using VisIt software.

4.5.3.4.2. 3D Search-Lattice File of Minimum F Value for Each Search Node

SELECTION OPTION: ***ilattice*** = 1

NAME: *<filein>_foslattice_out.3D*

FORMAT: text in Point3D format

This 3D optional output file of the search lattice containing the minimum *F* for each search node is generated when ***ilattice*** = 1. Following a simple header in Point3D format, each line in the 3D search-lattice file contains the x, y, z coordinates of the lattice node in the coordinate system of the DEM and the minimum factor of safety found for any trial surfaces centered at that node. Values in this file can differ from those in *<filein>_critfoslattice_out* file (section 4.5.3.4.1) for two reasons: (1) many of the lattice nodes may not represent the centers of critical surfaces but do have computed *F* values for other trial surfaces, and (2) some critical node values may be superseded by other trial surfaces with lower *F* values from less-stable parts of the DEM that have a critical node located elsewhere in the search space. If a search-lattice node did not yield any valid trial surfaces one of three values is assigned, as described in section 4.5.3.4.1 for the *<filein>_critfoslattice_out.3D* file. An excerpt of the output file is shown in figure 4.40 and a 3D visualization of an example of the complete 3D search-lattice file is shown in figure 4.41.

```
x_m y_m z_m F_Bish
558024.6317     5111496.1291     1000.0000 9999.0000
558024.6317     5111496.1291     1800.0000 9999.0000
558024.6317     5111496.1291     2600.0000 9999.0000
558024.6317     5111496.1291     3400.0000 9999.0000
558024.6317     5111496.1291     4200.0000 9999.0000
558024.6317     5111496.1291     5000.0000 9999.0000
558024.6317     5111496.1291     5800.0000 9999.0000
558024.6317     5111496.1291     6600.0000 9999.0000
558024.6317     5111496.1291     7400.0000 9999.0000
558024.6317     5111496.1291     8200.0000 9999.0000
558024.6317     5111496.1291     9000.0000 9999.0000
558824.6317     5111496.1291     1000.0000 9999.0000
558824.6317     5111496.1291     1800.0000 9999.0000
558824.6317     5111496.1291     2600.0000 9999.0000
558824.6317     5111496.1291     3400.0000 9999.0000
558824.6317     5111496.1291     4200.0000 9999.0000
558824.6317     5111496.1291     5000.0000 9999.0000
558824.6317     5111496.1291     5800.0000 9999.0000
558824.6317     5111496.1291     6600.0000 9999.0000
558824.6317     5111496.1291     7400.0000   7.3036
558824.6317     5111496.1291     8200.0000   7.4781
558824.6317     5111496.1291     9000.0000   7.7879
...
563024.6317     5118696.1291     4200.0000   2.2200
563024.6317     5118696.1291     4400.0000   2.2521
563224.6317     5118696.1291     3600.0000   2.2606
563224.6317     5118696.1291     4000.0000   2.2046
563224.6317     5118696.1291     4400.0000   2.2387
563424.6317     5118696.1291     3600.0000   2.2858
563424.6317     5118696.1291     3800.0000   2.2437
563424.6317     5118696.1291     4000.0000   2.2225
563424.6317     5118696.1291     4200.0000   2.2370
563424.6317     5118696.1291     4400.0000   2.2492
563424.6317     5118696.1291     4600.0000   2.2759
563424.6317     5118696.1291     4800.0000   2.2985
563624.6317     5118696.1291     4400.0000   2.2605
563624.6317     5118696.1291     4800.0000   2.2763
563824.6317     5118696.1291     4400.0000   2.2734
563824.6317     5118696.1291     4600.0000   2.2757
563824.6317     5118696.1291     4800.0000   2.2664
563824.6317     5118696.1291     5000.0000   2.2846
563824.6317     5118696.1291     5200.0000   2.3108
564024.6317     5118696.1291     4400.0000   2.3383
564024.6317     5118696.1291     4800.0000   2.2881
564024.6317     5118696.1291     5200.0000   2.3020
564224.6317     5118696.1291     4400.0000   2.4431
564224.6317     5118696.1291     4600.0000   2.3913
564224.6317     5118696.1291     4800.0000   2.3637
564224.6317     5118696.1291     5000.0000   2.3343
564224.6317     5118696.1291     5200.0000   2.3280
564224.6317     5118696.1291     5400.0000   2.3353
...
```

Figure 4.40. Text excerpts from a 3D search-lattice output file containing values for each lattice node. File from the Mount St. Helens example R displayed in figure 4.41 (file name: *R_sthel_foslattice_out.3D*); see section 7.6. File contents differ from the search-lattice output file highlighting the critical nodes shown in figure 4.39.

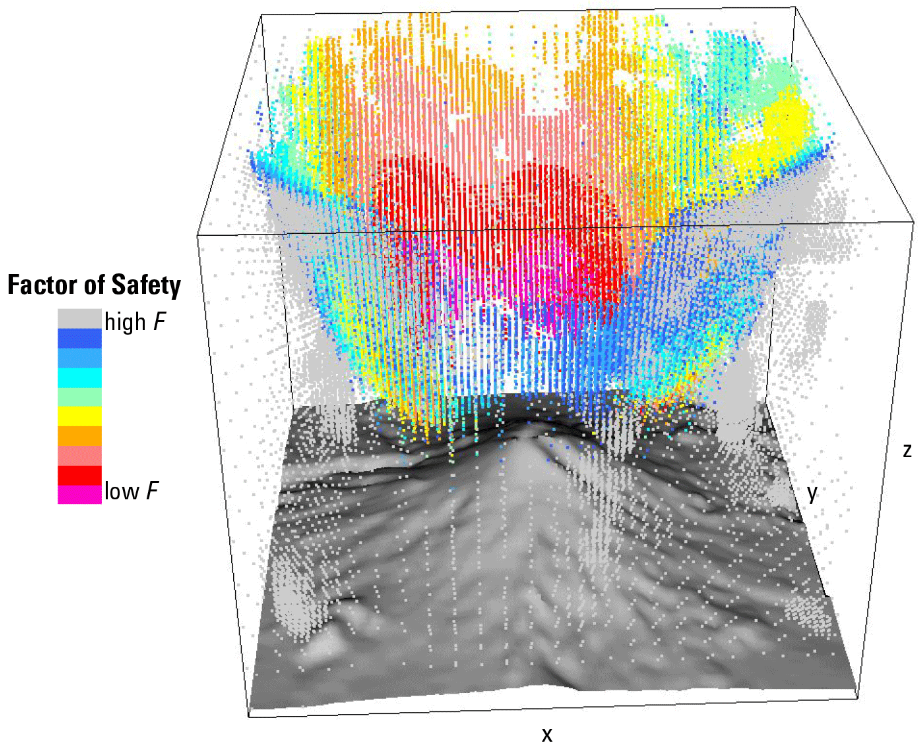


Figure 4.41. Image of 3D visualization of the minimum *F* found at each search-lattice node. File from the Mount St. Helens example R (file name: *R_sthel_foslattice_out.3D*) displayed above the DEM (file name: *sthel_res100mDEM.asc*); see section 7.6. The example uses a coarse-to-fine search. Image produced using VisIt software.

4.5.3.5. 3D Subsurface Factor-of-Safety File

SELECTION OPTION: ***isubsurf*** = 1, 2, or 3

NAME: *<filein>_subsurffos_out.3D* or *<filein>_subsurffos_out.txt*

FORMAT: text in Point3D format or Scoops3D formats

This optional 3D output file contains a 3D array of the minimum factor of safety, *F*, found at depth beneath each DEM cell and at a constant vertical spacing defined by ***zfrac***. It is created when ***isubsurf*** = 1, 2, or 3 (section 4.4.1.1.11.6) in the main parameter input file. Visualization of this file enables the user to identify continuous regions in the subsurface having similar values of *F*. Given the constant (regular) vertical spacing of the data in the file, there may or may not be an *F* value in the file for the exact ground-surface elevation at each DEM cell. Therefore, the file typically contains vertical values above the DEM surface. This allows 3D visualization software to smoothly portray *F* throughout the domain under the DEM surface (fig. 4.42). Using such software, the user can truncate the excess region above the DEM surface, if desired. Note that this file can become quite large if ***zfrac*** is small and (or) the dimensions of the DEM are large.

If ***isubsurf*** = 1 or 2, Scoops3D generates the output file *<filein>_subsurf_out.txt* with the location coordinates specified in either ijk (***isubsurf*** = 1) or xyz (***isubsurf*** = 2) format. For explanation of coordinate systems, see section 4.4.2.2.1. If ***isubsurf*** = 3, the file *<filein>_subsurf_out.3D* is generated with xyz coordinates, all specified in the coordinate system of the DEM, and a simplified header in Point3D format. The horizontal spacing of data within the file is equal to the DEM cell size and the vertical (depth) spacing is controlled by ***zfrac***. Examples of the three output options are shown in figure 4.43.

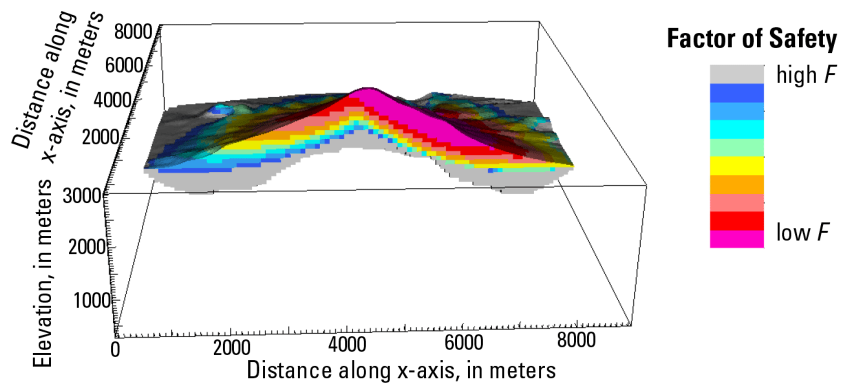


Figure 4.42. Image of 3D visualization of subsurface factors of safety. Ground surface truncated by topography and vertical slice to portray interior beneath the DEM. File from the Mount St. Helens example R (file name: *R_sthel_subsurffos_out.3D*); see section 7.6. Image created using VisIt software.

```
A
# Comments: Scoops3D Factors of safety in the subsurface
# Coordinate_system: ijk
# Field: 1 i
# Field: 2 j
# Field: 3 k
# Field: 4 F_Bish
# Length_units: m
# Grid_size:   96 x   91 x   28
# Grid_x_range:  557974.632 to  567574.632
# Grid_y_range: 5111446.129 to 5120546.129
# Grid_z_range:   256.155 to   3056.155
  6  91  1 9999.0000
  6  91  2 9999.0000
  6  91  3 9999.0000
  6  91  4 9999.0000
  6  91  5 9999.0000
  6  91  6 9999.0000
  6  91  7 9999.0000
  6  91  8  11.2456
  6  91  9  11.2456
  6  91  10  11.2456
  6  91  11  11.2456
  6  91  12  11.2456
...
B
# Comments: Scoops3D Factors of safety in the subsurface
# Coordinate_system: xyz
# Field: 1 x
# Field: 2 y
# Field: 3 z
# Field: 4 F_Bish
# Length_units: m
# Grid_size:   96 x   91 x   28
# Grid_x_range:  557974.632 to  567574.632
# Grid_y_range: 5111446.129 to 5120546.129
# Grid_z_range:   256.155 to   3056.155
     558524.620     5120496.000       306.155 9999.0000
     558524.620     5120496.000       406.155 9999.0000
     558524.620     5120496.000       506.155 9999.0000
     558524.620     5120496.000       606.155 9999.0000
     558524.620     5120496.000       706.155 9999.0000
...
C
x_m y_m z_m F_Bish
     558524.620     5120496.000       306.155 9999.0000
     558524.620     5120496.000       406.155 9999.0000
     558524.620     5120496.000       506.155 9999.0000
     558524.620     5120496.000       606.155 9999.0000
     558524.620     5120496.000       706.155 9999.0000
...
```

Figure 4.43. Text excerpts from three equivalent 3D subsurface factor-of-safety output files. Files from the Mount St. Helens example R (file name: *R_sthel_subsurffos_out*) in three user-selectable formats: *A,* ijk*, B,* xyz, and *C,* 3D or Point3D. Note that *B* and *C* are identical except for the header information. For these examples, ***zfrac*** = 1, so the vertical resolution for the <*filein*>*_subsurffos_out* files is equal to the DEM resolution (100 m).

Chapter 5. Practical Considerations

Ultimately, the user would like to ensure that all of the important parts of the DEM have accurate stability assessments that are computed in an acceptable amount of time. This chapter and associated reference tables (tables 5.1, 5.2, and 5.3) provide guidelines to assure solution quality and thorough searches of the DEM. In addition, we provide guidelines for reducing excessive computer runtime (section 5.2). The seven factors listed in table 5.1 control the balance between the solution and search quality and the computational effort expended on a Scoops3D analysis.

Table 5.1. List of factors influencing the thoroughness and accuracy of a 3D stability assessment in Scoops3D.

[Section references and basic methods for assessing the effects are shown for each factor]

Factor	Section	Method of assessment
Subsurface conditions	5.3.1	Assess λ values as they relate to potential failure size limits
Potential failure size limits	5.3.2	Examine critical-size check file (*<filein>_critcheck_out.asc*), one of the search quality files
DEM extent	5.3.3	Attempt Scoops3D run and determine if computer runtime or memory are limitations
DEM resolution	5.3.4	Examine number of columns file (*<filein>_numcols_out.asc*), one of the search quality files
Search-lattice extent	5.3.5	Examine search-lattice boundary check (*<filein>_boundcheck_out.asc*) and (or) critical search-lattice *(<filein>_foslatticecrit_out.3D*) files
Search resolution	5.3.6	Trial and error. Compare factor of safety (*<filein>_fos3d_out.asc*) and critical size files with results from different search resolutions
Poor solutions	5.3.7	Examine factor of safety (*<filein>_fos3d_out.asc*) and number of filtered surfaces (*<filein>_filtergrid_out.asc*) files

Interactions between the factors in table 5.1 can be complex. Typically, actions that improve solution quality and thoroughness of the search are the opposite of actions that decrease computational effort and memory requirements (tables 5.2 and 5.3). Adjusting one factor without accounting for the effects of the other factors can lead to unintended consequences in the slope-stability results. Despite the complex interaction between factors, the user can obtain good results by applying the guidelines provided in this chapter. Table 5.2 provides suggested actions to achieve specific goals, and references to related sections in this chapter, whereas table 5.3 presents the effect that selected actions may have on solution quality, thoroughness of search, computational effort, and computer memory requirements.

Table 5.2. List of suggestions to improve solution quality, improve thoroughness of search, reduce computational effort, and reduce memory requirements in an analysis performed by Scoops3D.

[Each suggestion references a subsection in this chapter for more information, as well as listing the window in Scoops3D-i or parameter(s) in the main parameter input file that controls the suggested action]

Desired goal	Section	Action	Location in Scoops3D-i	Modification of Scoops3Dinput parameters
Improve solution quality	5.3.7	Filter poor solutions	**Options > Advanced Parameters**	Assign value for ***absminma***
	5.3.4	Increase DEM resolution	Performed outside of Scoops3D-i	Not applicable
Improve thoroughness of search	5.3.5	Increase vertical extent of search lattice[1]	**Search Configuration**	Decrease ***zsmin*** and/or increase ***zsmax***
	5.3.5	Increase horizontal extent of search lattice[1]	**Search Configuration**	Decrease ***ismin*** and/or ***jsmin*** or increase ***ismax*** and/or ***jsmax***
	5.3.6	Increase vertical resolution of search lattice	**Search Configuration**	Increase ***zsrchres***
	5.3.6	Increase horizontal resolution of search lattice	**Search Configuration**	Increase ***nsrchres***
	5.3.2	Increase potential failure size range[1]	**Search Configuration**	Increase range of ***armin***, ***armax*** or ***vmin***, ***max***
	5.3.6	Decrease radius increment	**Search Configuration**	Decrease ***dr***
Reduce computational effort	5.3.6	Use coarse-to-fine search	**Search Configuration > Advanced**	***irefine*** = 1, adjust ***multres***
	5.3.6	Decrease number of slip directions	**Search Configuration**	Decrease ***numdir*** and/or ***deginc***
	5.3.6	Decrease vertical resolution of search lattice	**Search Configuration**	Decrease ***zsrchres***
	5.3.6	Decrease horizontal resolution of search lattice	**Search Configuration**	Decrease ***nsrchres***
	5.3.5	Decrease vertical extent of search lattice	**Search Configuration**	Increase ***zsmin*** and/or decrease ***zsmax***
	5.3.5	Decrease horizontal extent of search lattice	**Search Configuration**	Increase ***ismin*** and/or ***jsmin*** or decrease ***ismax*** and/or ***jsmax***
	5.3.5	Use search file to decrease horizontal extent of search lattice	**Search method**	***srch*** = 'file' (requires creation of additional file)
	5.3.6	Increase radius increment	**Search Configuration**	Increase ***dr***
	5.3.2	Decrease potential failure size range	**Search Configuration**	Reduce range of ***armin***, ***armax*** or ***vmin***, ***vmax***
	5.3.3	Decrease extent of DEM	Performed outside of Scoops3D-i	Not applicable
	5.3.4	Decrease DEM resolution	Performed outside of Scoops3D-i	Not applicable
Reduce memory requirements	5.3.5	Decrease vertical extent of search lattice	**Search Configuration**	Increase ***zsmin*** and/or decrease ***zsmax***
	5.3.6	Decrease vertical resolution of search lattice	**Search Configuration**	Decrease ***zsrchres***
	5.3.6	Decrease horizontal resolution of search lattice	**Search Configuration**	Decrease ***nsrchres***
	5.3.6	Use simple search instead of coarse-to-fine search	**Search Configuration > Advanced**	***irefine*** = 0
	5.3.3	Decrease extent of DEM	Performed outside of Scoops3D-i	Not applicable
	5.3.5	Decrease horizontal extent of search lattice	**Search Configuration**	Increase ***ismin*** and/or ***jsmin*** or decrease ***ismax*** and/or ***jsmax***
	5.3.4	Decrease DEM resolution	Performed outside of Scoops3D-i	Not applicable
	5.2	Deselect specific optional output files	**Options > Output Files**	***isubsurf*** = 0, ***isqout*** = 0, ***irelfos***= 0

[1]This action may or may not improve the thoroughness of a search. The user should examine related output files (table 5.1) to determine if a specific action is an improvement.

Table 5.3. List of the effects of different actions on solution quality, thoroughness of search, computational effort (runtime), and computer memory requirements in an analysis performed by Scoops3D.

[Note that improving quality and thoroughness are typically at odds with decreasing computational effort and memory requirements. Some actions will have no effect and are indicated by '–']

Action	Solution quality	Thoroughness of search	Computational effort	Memory requirements
Potential failure size limits				
Increase size range	–	Improve[1]	Increase	–
Decrease size range	–	Degrade[1]	Decrease	–
DEM extent[2]				
Increase extent	–	–	Increase	Increase
Decrease extent	–	–	Decrease	Decrease
DEM resolution[2]				
Increase resolution	Improve	Improve[3]	Increase	Increase
Decrease resolution	Degrade	Degrade[3]	Decrease	Decrease
Search-lattice extent				
Increase horizontal extent	–	Improve[1]	Increase	Slight increase[4]
Decrease horizontal extent	–	Degrade[1]	Decrease	Slight decrease[4]
Increase vertical extent	–	Improve[1]	Increase	Increase[4]
Decrease vertical extent	–	Degrade[1]	Decrease	Decrease[4]
Search resolution				
Select coarse-to-fine search	–	Most likely the same	Significant decrease	Increase
Select simple search	–	Improve in rare cases	Significant increase	Decrease
Increase horizontal resolution	–	Improve	Increase	Slight increase
Decrease horizontal resolution	–	Degrade	Decrease	Slight decrease
Increase vertical resolution	–	Improve	Increase	Increase[4]
Decrease vertical resolution	–	Degrade	Decrease	Decrease[4]
Increase radius increment	–	Degrade	Decrease	–
Decrease radius increment	–	Improve	Increase	–
Increase number of slip directions	–	Improve[1]	Increase	–
Decrease number of slip directions	–	Degrade[1]	Decrease	–
Other actions				
Filter solutions using m_α [5]	Potential improvement	No effect	Potential decrease	–
Deselect specific optional output files	–	–	–	Decrease

[1]Some actions will increase the number of trial surfaces, but may not be necessary for a thorough search.

[2]Changes to the DEM are performed outside of Scoops3D and require modification of associated raster input files (for example, layers or piezometric surfaces) and 3D files

[3]Increased DEM resolution increases horizontal search resolution, but is not generally recommended for improved thoroughness of a search.

[4]Some changes to search lattice affect memory requirements only when using a coarse-to-fine search.

[5] m_α is part of the computation of normal force acting on a trial slip surface, used in Bishop's simplified method of analysis.

5.1. Assess Solution and Search Quality

Scoops3D can provide slope-stability assessments (including minimum factor of safety and associated potential failure size for each DEM cell) for a range of 3D searches. However, the overall quality of the results may vary. For a given Scoops3D analysis, the user needs to assess: (1) solution quality and (2) thoroughness of the search. Solution quality refers to the accuracy of the factor of safety and size calculations for an individual potential failure mass, relative to solutions using large numbers of active columns. A poor solution can result owing to an insufficient number of active columns in a potential failure mass (section 5.3.4) or to convergence problems with Bishop's simplified method (section 5.3.7). Thoroughness of the search refers to the process of analyzing enough trial surfaces, in the appropriate user-defined size range, to determine the minimum factor of safety for every DEM cell. Search thoroughness is affected by the extent of the search lattice (section 5.3.5) and resolution of the search (section 5.3.6). Table 5.2 lists actions to achieve better solution quality and search thoroughness using Scoops3D, with references to the pertinent sections of this chapter. Potential effects of these actions are listed in table 5.3. Improving solution or search quality will most likely increase computer runtime and memory requirements.

The quality of results desired by the user may vary from project to project. In some cases, only an approximation of the factor of safety may be needed, whereas in other cases precise computations of potential failure volumes may be necessary. Note that Scoops3D can often provide reasonable estimates of factor of safety with relatively coarse DEMs and sparse search lattices. Precise volume computations require higher resolution DEMs, with appropriate resolution dependent on the potential failure sizes analyzed. Before assessing the quality of the overall analysis, the user needs to identify the areas of interest in the DEM and determine the degree of solution certainty required. Scoops3D will not thoroughly assess factors of safety at the edges of a DEM, as any trial surfaces that intersect the boundaries are discarded.

To build confidence in the overall solution and search quality provided by Scoops3D, the user can examine each of the main items listed in table 5.1. If the quality or confidence in any factors appear to be subpar for the user's needs, then adjustments can be made as necessary. Typically, a systematic examination requires a series of trial-and-error runs to fully evaluate the results. Initially, the user will likely make "best guesses" for each parameter, run Scoops3D, examine the output (including the quality files described below), and make adjustments as needed. Some of the controlling factors can be assessed using output files; others (such as search resolution) need to be assessed by comparing a series of analyses with different resolutions. Details for assessing each controlling factor are discussed in section 5.3.

In some cases, it may be more effective for the user to initially analyze a subset of the DEM by limiting the search lattice to a smaller horizontal extent. A smaller search lattice enables faster computation and therefore more efficient examination of the controlling factors. Once appropriate levels for the different factors are identified, the user can implement these for analysis of the entire DEM. For completeness, the factors listed in table 5.1 should then be re-examined using results from the entire DEM and adjusted as necessary. Note also that changes in conditions for a given DEM, such as adding pore pressures or earthquake loading, may necessitate modifying some of the analysis factors in table 5.1.

5.2. Reduce Computer Runtime and Memory Requirements

For some analyses, a user may find that Scoops3D takes an excessively long time to finish executing. Runs using DEMs that contain many cells and that utilize extensive, high-resolution search lattices may take hours to days for Scoops3D to finish execution, even on a relatively fast computer with extensive memory. Table 5.2 provides some suggestions to reduce computer runtime or memory requirements. Note that these actions may reduce solution quality and search thoroughness (table 5.3); in the end the user may need to choose an acceptable compromise.

Improvements in runtime can commonly be achieved by reducing the number of trial surfaces computed (by reducing the search lattice resolution or extent) (fig. 5.1*A*) and (or) the number of active columns (by increasing the DEM cell size) contained in each potential failure mass (table 5.3). The simplest approach for reducing runtime is to select the coarse-to-fine search option and set the horizontal multiplier to a value greater than one (unless the DEM resolution is extremely coarse, this value may be $\geq$4). We suggest an initial vertical resolution equal to the horizontal multiplier times the DEM cell size. Some trial-and-error tests may be needed to determine search-lattice resolutions and radius increments that run quickly yet provide reasonable results (5.3.6). In addition, runtime may be reduced by decreasing the extent of the search lattice (provided the areas of interest are still assessed) or by decreasing the range of potential failure sizes, if appropriate to the problem. Increasing the size of the DEM cells (decreasing its resolution) may help as well, so long as enough active columns are maintained in the potential failure masses for a reasonable computation of *F* and size. However, modifying the DEM resolution or extent may involve considerable effort by the user, as all associated grids and arrays (for example, those for piezometric surface, layers, 3D pressure head or 3D materials) will need to be modified in a GIS or other software. Decreasing the number of slip directions or increasing the radius increment will also reduce runtime.

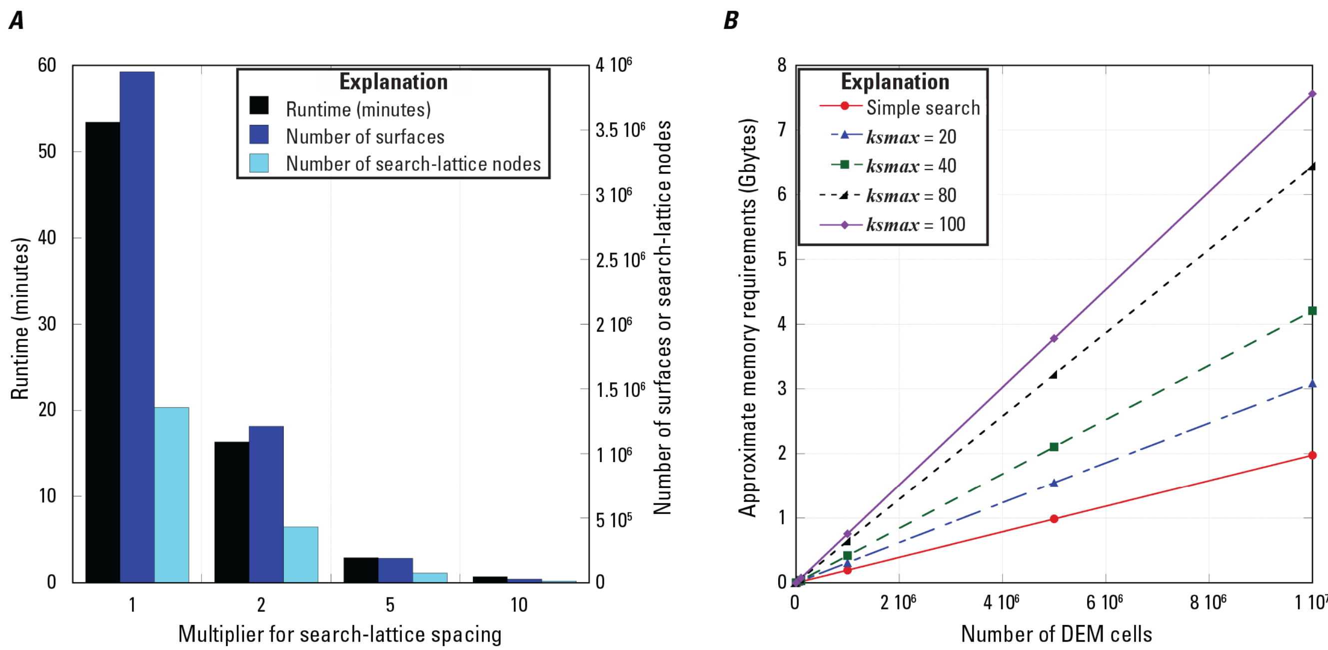


Figure 5.1. Graphs showing examples of computer runtime and approximate memory requirements using Scoops3D. *A*, Comparison of runtime, number of trial surfaces, and number of search-lattice nodes related to the horizontal and vertical search-lattice resolution, described as a multiplier of the DEM cell size. The runtimes are based on variations of Scoops3D example file *Q_seadry.scp* (section 7.5). Analyses were performed on an Intel Xeon W3690, 3.47 GHz processer running the Windows 7 operating system. *B*, Approximate computer memory needed for differing sizes of DEMs, assuming the horizontal spacing of the search-lattice nodes equals the DEM cell size (***nsrchres*** = 1). The vertical lattice spacing is a factor of ksmax (defined as the integer of ((***zsmax-zsmin***)/***zsrchres***) +1). Lattices with larger ksmax values have more nodes.

If computer memory requirements are halting execution, the user may decrease the extent and (or) resolution of the DEM, resulting in a reduced number of DEM cells (fig. 5.1*B*) as well as a reduced number of cells in any associated raster grids and (or) 3D files. The coarse-to-fine search option also requires more memory. At the cost of increased runtime, the user may select a simple search instead. Alternatively, if the coarse-to-fine search option is selected, memory requirements can be reduced by decreasing the vertical extent (if appropriate) or vertical resolution of the search lattice. Modification of the horizontal extent or resolution of the search lattice only modestly reduces memory requirements. If an extensive, high-resolution lattice is necessary for a thorough search, the user can run several analyses using adjacent regions (laterally and [or] vertically) of the search lattice and then combine the results by creating a composite factor-of-safety map containing the minimum values from the multiple runs. In addition, the user can reduce memory requirements by not selecting several of the optional output files; creating a 3D subsurface *F* file (***isubsurf***) uses the most memory. Not selecting the search quality files (***isqout***) and relative *F* file (***irelfos***) will slightly reduce memory requirements.

Note, in contrast to 64-bit operating systems, 32-bit computer operating systems typically have a significantly smaller memory limit for a single task, such as executing Scoops3D.

5.3. Control Factors

Although all of the controlling factors listed in table 5.1 play a role in a Scoops3D analysis, several items (subsurface conditions, size limits, extent of DEM) relate directly to the physical set-up of the problem, whereas others (for example, search lattice resolution and extent) influence the thoroughness of the search process. In the following sections, we first discuss those factors involved with the physical set-up of the problem and then discuss the factors controlling the solution and search quality.

5.3.1. Subsurface Conditions

Subsurface conditions, such as material strength and pore-water pressures, are typically defined by the problem of interest. Nevertheless, these factors influence the size and location of the computed critical surfaces, which may compel the user to modify the other factors listed in table 5.1. The user should be aware of these effects when selecting subsurface values; slight modifications of some factors may lead to more satisfactory results. For example, strength parameters have a large effect on the depth of the least stable, or critical, trial surface and thus influence potential failure volume and surface area. This can be seen using the non-dimensional ratio λ, an index of cohesive to frictional strength:

$$\lambda = \frac{c}{\gamma H \tan\phi}, \qquad (5.1)$$

where c is cohesion, γ is material unit weight, H is hillslope height, and ϕ is angle of internal friction (Janbu, 1954).

Critical surfaces obtained for different values of λ, given a 10 m high, 30° embankment (example provided in section 6.2.1) are shown in figure 5.2. For larger values of λ (relatively more cohesive strength), the critical surface is deeper and the associated volume greater. For dry, cohesionless materials (λ = 0), the critical surface is always shallow with minimal volume. Thus, the user should be aware that using purely frictional strength with no pore pressures will result in shallow critical surfaces and the least-stable areas will likely merely reflect steep areas in the topography. Moreover, least-stable potential failure masses in friction-dominated materials will tend to approach, and may be constrained by, the user-defined lower size limits for potential failures.

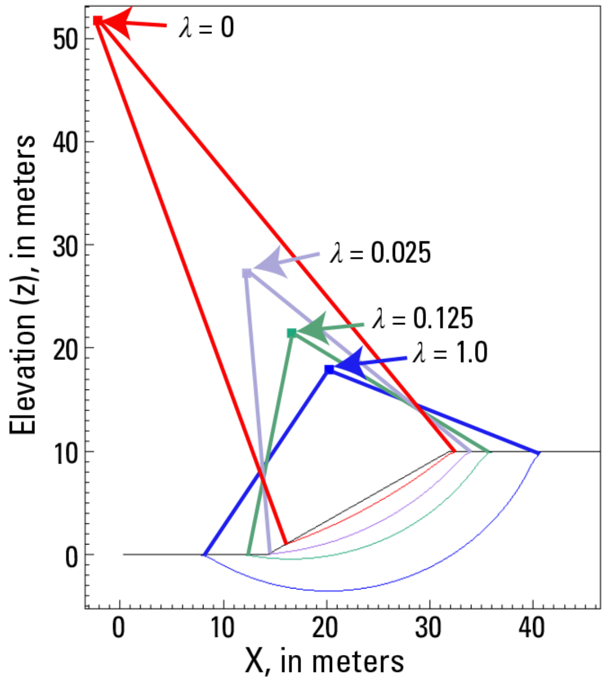


Figure 5.2. Cross section showing critical potential failure surfaces for a dry embankment with different values of λ. The 10 m high, 30° embankment is described in section 6.2.1. Strength properties and λ values are defined in table 6.3, with the addition of a critical surface for $\lambda = 0$ (c = 0 kPa, ϕ = 10°, and γ = 17 kN/m^3). Materials with relatively less cohesion (lower λ) have shallower critical surfaces with smaller volumes. The potential failure surface for λ = 0 is the critical surface with a volume larger than 100 m^3; smaller volume restrictions yield smaller and slightly less stable potential failures.

High pore-water pressures at depth can lead to larger, deeper critical surfaces. Computed factors of safety can be quite sensitive to pore pressures and excessively high pressures can occasionally lead to unrealistically low values of factor of safety when using Bishop's simplified method of analysis. Potentially unrealistic, high pressures can stem from selection of a large value of r_u, a piezometric surface above the ground surface (perhaps affecting only part of the domain), or locally high pressures in a 3D pressure-head file. Thus, the user should exercise diligence when incorporating pore-pressure effects and be aware of any local anomalies in stability resulting from locally high pore pressure (see section 5.3.7).

5.3.2. Potential Failure Size Limits

Before performing a Scoops3D analysis, the user must select the minimum and maximum potential failure sizes (either volumes or areas) to be analyzed. These limits may be identified on the basis of field observations of past failures or selected on the basis of sizes of interest to the user.

If the user wants to find the ultimate minimum factor of safety for each DEM cell, we recommend a search that is not constrained by the size limits. If a restrictive size range is selected, the critical surfaces may be outside of this range. Constraints on the critical surfaces can be identified using the critical-size check file (*<filein>_critcheck_out.asc*), one of the optional search quality output files. This file contains an array indicating whether the critical potential failure for each DEM cell was restricted by the user-defined size limits (either volume or area, depending on the primary criterion selected). Section 4.5.3.2.1 provides a description of the values in this file. Examples displaying three different critical-size check files for searches that are: (*A*) restricted by the maximum size limit, (*B*) restricted by the minimum size limit, and (*C*) unrestricted in the area of interest, are shown in figure 5.3. If the user is only concerned with a very specific size range, it may be acceptable to have some critical potential failures at the size limits.

Our experience is that the potential failure size range for a given analysis typically should vary no more than about 1–2 orders of magnitude, provided the range brackets the critical sizes, otherwise a thorough search may require excessive effort to compute the stability of numerous trial surfaces between the minimum and maximum sizes. If the user wants to analyze more potential failure size ranges, we suggest performing multiple analyses, each with a different size range.

In addition, size limits for potential failures can greatly affect the required DEM resolution as well as the search resolution and extent needed for a thorough analysis. For example, large potential failures may only need a coarse (low) resolution DEM with a relatively large search-lattice extent. In this case, a finer (higher) resolution DEM would provide good factor-of-safety solutions, but might lead to excessive computation time. Conversely, small potential failures may need a higher-resolution search and DEM to provide accurate results. These issues are discussed further in sections 5.3.4 and 5.3.6.

Another possible problem related to the potential failure size is the number of valid subsets, in the user-specified size range, found for a given search-lattice node and radius (fig. 3.3). For a given radius, Scoops3D may find multiple trial surfaces affecting different parts of the DEM (section 3.2.1). In some cases, it is possible to exceed the number of subsets currently allowed in Scoops3D. If the number of subsets exceeds 10, the user will receive a warning message, but Scoops3D will not halt execution. This warning indicates that a single sphere creates more than 10 separate valid trial surfaces. An occasional occurrence of this message is not of concern, but if this message occurs repeatedly then parts of the DEM may not have been thoroughly analyzed. In practice, this situation is rare but may indicate a problem with DEM resolution or range of potential failure sizes.

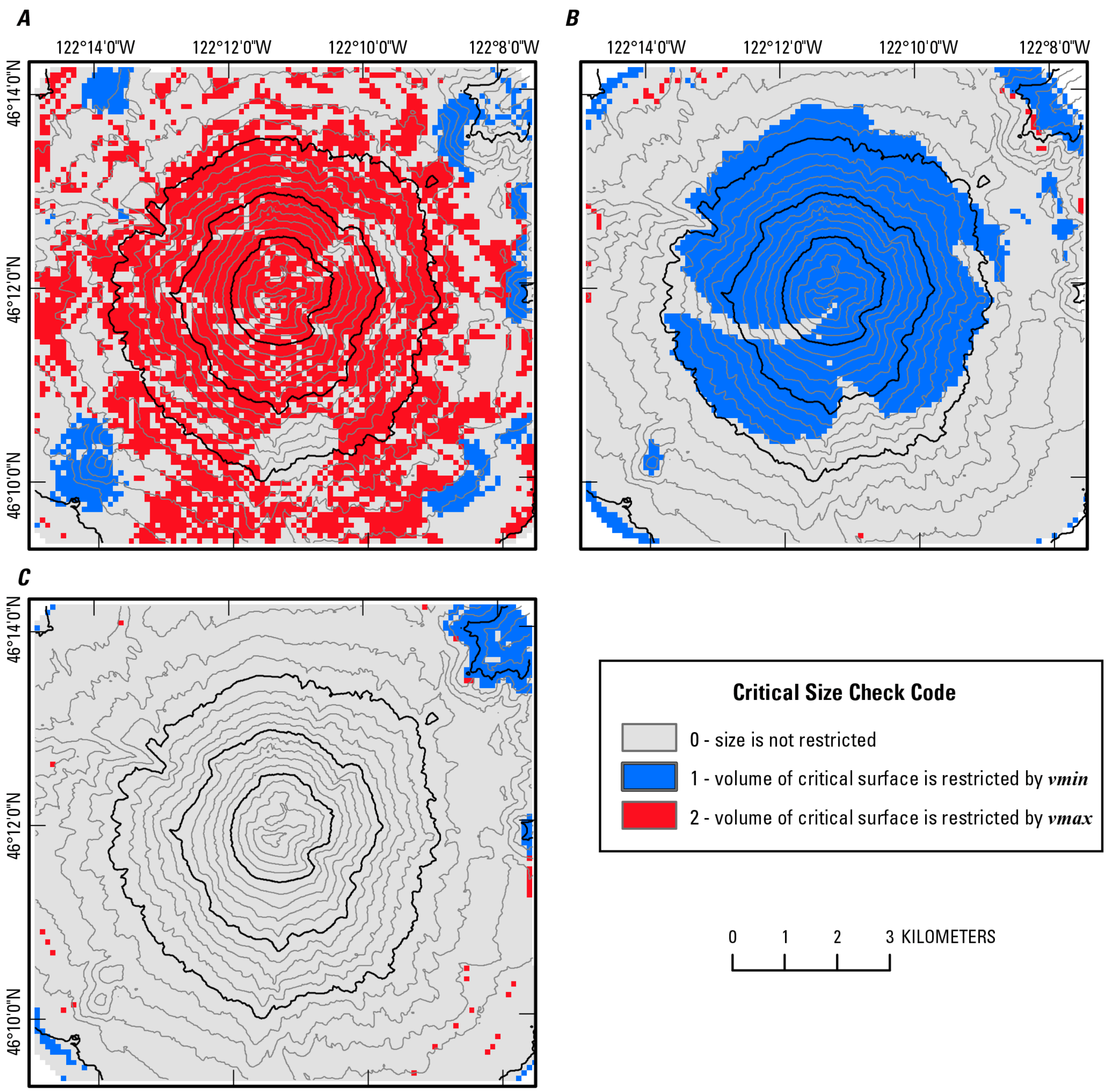


Figure 5.3. Maps illustrating restrictions on the size of the critical surfaces for potential failure masses found in three different Scoops3D analyses. Volume was selected as the primary size criterion. Data portrayed are contained in critical-size check output files (*<filein>_critcheck_out.asc*). Examples are derived from the Mount St. Helens example R (see section 7.6) by modifying the range of potential failure volumes. The 100 m contour lines are derived from the DEM. Critical surfaces found for the red DEM cells are at the user-defined maximum volume (***critcheck*** = 2); those in blue are at the minimum volume (***critcheck*** = 1). *A*, Case with ***vmax*** for potential failures set too small and numerous critical sizes are at the maximum size limit, ***vmax*** (***vmin*** = 0.5×10^8 m^3 and ***vmax*** = 0.2×10^9 m^3). *B*, Case with ***vmin*** for potential failures set too large and numerous critical sizes are at the minimum size limit, ***vmin*** (***vmin*** = 1×10^9 m^3 and ***vmax*** = 5×10^9 m^3). *C*, Case with no size restrictions in the areas of interest (***vmin*** = 0.1×10^9 m^3 and ***vmax*** = 3.5×10^9 m^3, example *R_sthel.scp*). Note that the edges of the DEM are considered less important and commonly have size restrictions. Maps created using Esri ArcMap software.

5.3.3. DEM Extent

The extent of the DEM to be analyzed is also part of the initial physical set-up. Typically, the user is interested in assessing the stability of a specific region. Two issues are germane when selecting a DEM: (1) the overall extent and (2) the amount of buffer around the area of interest. Performing a thorough search of a DEM with many cells may be computationally intensive, both in computer runtime and memory usage (fig. 5.1). Because the sizes of the computational arrays used by Scoops3D are controlled by the number of DEM cells, overall memory usage expands as the DEM extent increases. The user may need to decrease the extent of the DEM to fit within the memory limits of their computer and (or) to permit reasonable runtimes. If the user wants to assess large areas, it may be necessary to perform several analyses with smaller, overlapping DEMs and then merge the results. Alternatively, the user may perform a preliminary analysis with a coarse DEM and then further examine areas of interest using smaller, finer resolution DEMs.

In addition, the user should ensure that the DEM includes cells that extend beyond the primary area of interest – a buffer area, typically near the boundaries of the domain. This buffer is needed for two reasons. To accurately compute stability for a range of potential failure sizes, the DEM needs to include terrain beyond the precise area of interest. In addition, cells near the DEM boundaries may be included only in a limited number of trial surfaces, as any trial surface that intersects the boundaries is discarded. Thus, DEM cells near the boundaries are not fully analyzed for least-stable surfaces, and the user should be aware that computed factors of safety for these boundary cells might not be the minimums compared to those determined using a more extensive DEM. Commonly, we have found that the buffer area should be a minimum of 10 DEM cells, although the extent for a particular analysis depends on DEM cell size, material strength, and potential failure size limits.

5.3.4. DEM Resolution

Potential failure masses with too few active columns (defined by the DEM cells) result in poor approximations of the potential failure geometry, slip surface area, and volume, and thus poorer calculations of factor of safety. Increasing the resolution of the DEM provides more active columns (from both full and partial columns) for a given trial surface and thereby increases the accuracy of factor of safety, as well as volume and area, calculations. We have found that, for most homogeneous slopes, Scoops3D needs a trial surface that includes at least ~200 active columns to provide adequate results in computed factor of safety (within 1 percent) and volume (within 2 percent) compared to a solution using tens of thousands of columns (fig. 5.4 and section 6.6). However, trial surfaces with ~100 active columns may provide adequate factor-of-safety values. Note that Scoops3D can find reasonable factors of safety even with coarser DEM grids; however, these coarse grids may reduce the accuracy of computed potential failure sizes. Potential failures in steep terrain, with only cohesive strength, or with complex subsurface distributions of material properties and pore-water pressures may require more active columns (at least 300 to 500) within the potential failure mass to provide accurate solutions of both factor of safety and volume (see section 6.6).

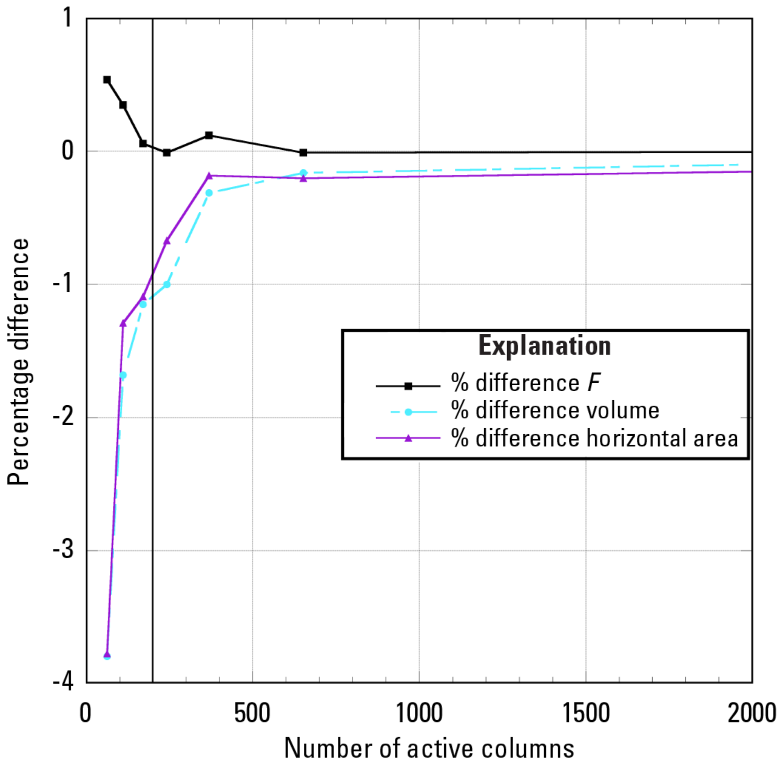


Figure 5.4. Graph showing an example of the differences in computed 3D factor of safety, volume, and horizontal area as the number of active columns varies. Example uses the potential failure mass with the global minimum factor of safety from the Mount St. Helens example R (section 7.6). Differences are relative to values obtained with a very high-resolution DEM, where the potential failure mass contains 10,106 active columns. Vertical line denotes 200 active columns. Differences in all results are <1 percent for potential failure masses with >200 active columns.

By performing an initial analysis, the user can readily examine whether the DEM has sufficient resolution to provide potential failure masses with a user-defined minimum number of active columns (set by the parameter ***limcol***; the Scoops3D-i default is 100). The main output file (*<filein>_out.txt*, section 4.5.1.1) lists the number of potential failure masses with active column totals less than ***limcol*** and the column warning output file (*<filein>_ncollerr_out.txt*, section 4.5.2.2) lists details regarding all trial surfaces (not just the critical surfaces) that contain less than the specified number of active columns. Note that Scoops3D does not halt execution if a surface has fewer active columns. If many surfaces contain less the desired number of active columns, it may be helpful to examine the optional search quality file (*<filein>_numcols_out.asc*), containing a raster grid recording the number of columns included in the critical surface affecting each DEM cell (fig. 5.5), to see whether a large number of critical surfaces contained too few active columns, particularly in areas of interest.

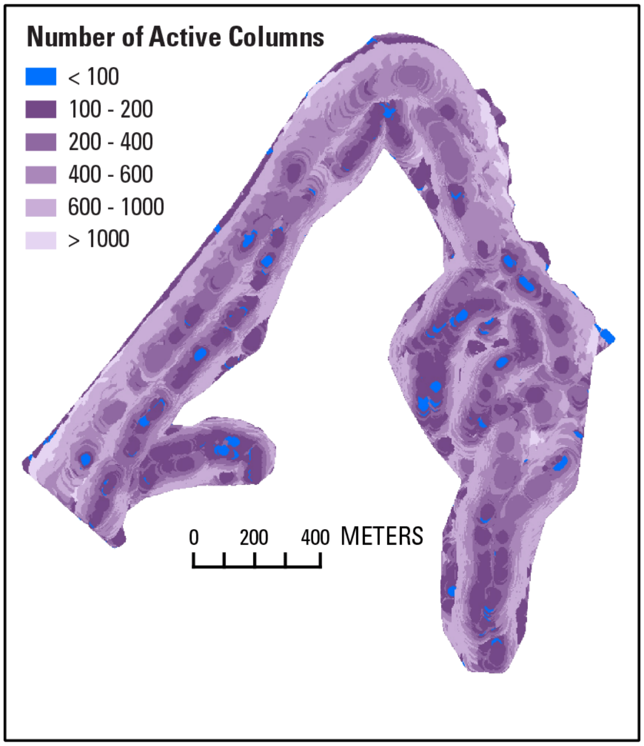


Figure 5.5. Map showing the number of active columns intersected by the critical surfaces for each DEM cell. Data portrayed are contained in the number of columns output file for Seattle example P (file name: *P_seadry_numcols_out.asc*); see section 7.5. DEM cells highlighted in blue have a critical surface affecting less than 100 active columns. Factors of safety and volumes for these critical surfaces may not be as accurate as critical surfaces with more active columns. Map created using QGIS software.

Some surfaces with too few active columns will be unlikely to alter the overall results greatly, particularly if they are just trial surfaces and not critical surfaces. If there are large numbers of critical surfaces with too few active columns, however, then the resolution of the DEM is likely too low. To correct this, the user can either obtain a different, higher resolution DEM with smaller cell sizes or resample the original DEM to a higher resolution (smaller cell size). Although resampling may improve the accuracy of the factor-of-safety solutions, it will not provide any more actual topographic detail and the resulting DEM is merely smoothed; this effect may or may not be desirable depending on the likelihood of the smoothed topography being important to potential failures. Note that it usually better to resample from the original DEM rather than further resample an already resampled DEM. If the DEM resolution is modified, all associated files (other raster grids and 3D arrays) should be modified as well.

On the other hand, if most of the critical surfaces contain more than a thousand active columns, Scoops3D is likely performing extra computational work. This may be acceptable if the user has a fast computer with sufficient memory. If not, resampling the DEM to a coarser overall resolution will improve computational efficiency. Obtaining an optimal DEM resolution for a particular setting may require a bit of trial and error, and is dependent on the potential failure sizes of interest.

5.3.5. Search-Lattice Extent

A thorough search requires that the search lattice is of sufficient lateral and vertical extent so that all areas of interest are encompassed by trial surfaces with the lowest computed factor of safety. A 3D search in Scoops3D involves more than just determining the global (or overall) minimum factor of safety – local minima must be determined for each DEM cell of interest to the user. However, if Scoops3D is performing a search with an excessively large lattice, the user may want to trim the lattice extent so that unnecessary effort will not be expended computing the stability of trial surfaces that are not critical surfaces. Typically, a coarse-to-fine search (the recommended option) with a small amount of "excess" lattice will not greatly affect run time, as most of the excess nodes will be ignored. If the user wants to search an irregularly shaped search lattice, a search file can be used to define the horizontal extent of the lattice (section 4.4.2.1.3), thereby limiting computational effort. A common problem is a lattice that is too restrictive for a thorough search. Below, we first suggest reasonable initial settings for the lattice extent and then describe tools that enable the user to assess the thoroughness of the search for a given lattice extent.

A reasonable initial estimate for the horizontal extent of the search lattice is an extent equal to that of the DEM (Scoops3D-i option – "Use extents from DEM header"). The horizontal extent can be adjusted in subsequent runs if needed. There are cases, commonly with large trial surfaces or steep slopes near a DEM boundary, where the horizontal extent of the search lattice should extend beyond the DEM limits (fig. 5.6).

The upper vertical limit to the search lattice can be more difficult to define. To provide a thorough search, we have found that the upper limit of the search lattice should typically extend 2 to 10 times the relief of the topography. Flatter slopes commonly need higher vertical limits, relative to their topographic relief (fig. 5.7). We suggest that the user initially use a lattice that extends an amount twice the topographic relief above the highest point in the topography (for example, if the relief is 1000 m and the highest elevation is 4000 m, then the upper vertical limit of the search lattice would be at an elevation of 6000 m). For a lower limit, we suggest an initial estimate of approximately half of the relief above the lowest point in the topography (3500 m for the example described above). The user may need to revise these lattice limits after examining the optional output files described below.

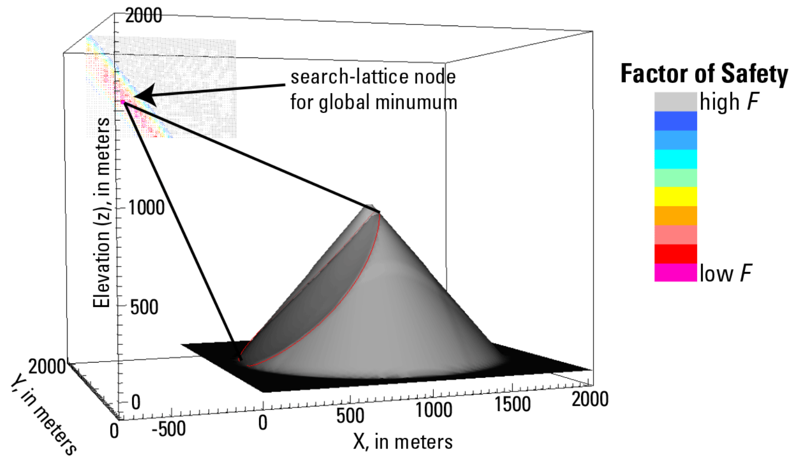


Figure 5.6. Perspective view of a cone illustrating a critical search-lattice node beyond the horizontal limits of the DEM. Factor-of-safety (*F*) values for part of the search-lattice nodes (using the ***ilattice*** output option) are shown in colors. Cone is 1,000 m high and slopes 50°; the critical surface for the overall least-stable surface (global minimum) is outlined in red. Details of the cone example are described in section 6.2.2. Image created using VisIt software.

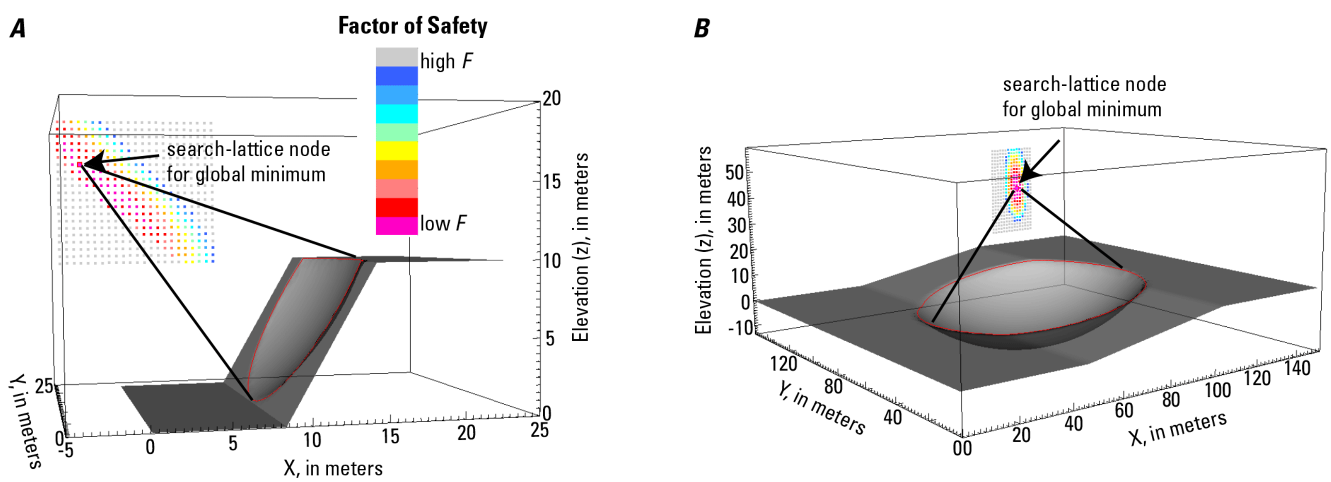
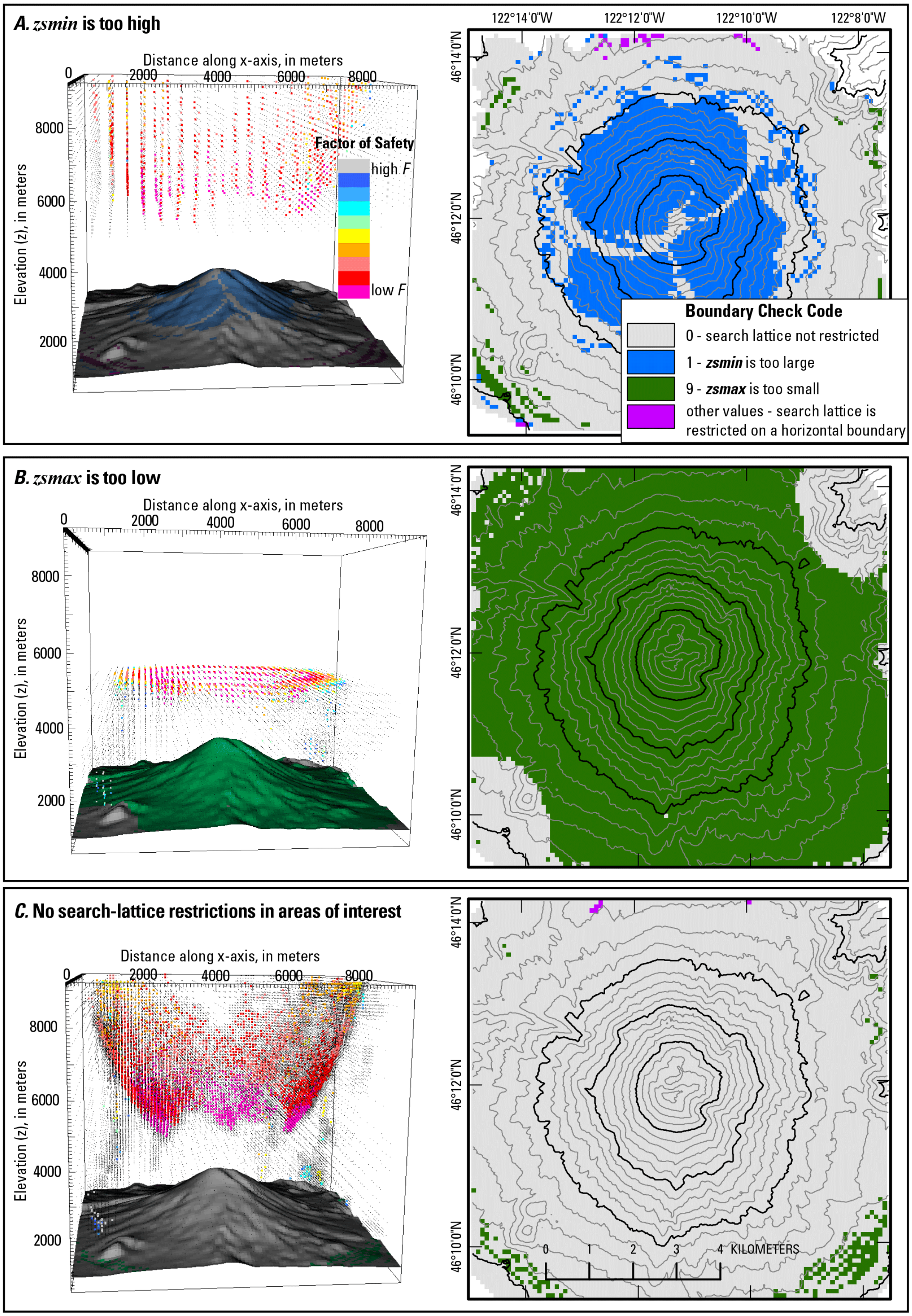


Figure 5.7. Perspective views of two DEMs showing the location of the critical search-lattice node relative to topographic relief. For each DEM, one slice through the search lattice highlights the node with the overall least-stable surface (global minimum *F*); *F* values for search-lattice nodes obtained using the ***ilattice*** output option. *A*, 10 m high, 60° embankment, critical node for global minimum is located at an elevation of ~15 m (~1.5X the relief). *B*, 10 m high, 10° embankment, critical node for global minimum is located at an elevation of ~45 m (~4.5X the relief). Note that gentler topography (*B*) commonly requires a search lattice that extends higher (relative to the topographic relief) to encompass nodes for the global minimum *F*. Details of the embankment examples are described in sections 6.2.1 and 6.3.1. Images created using VisIt software.

When performing an initial analysis, the user can instruct Scoops3D to provide two optional files for examining whether the search lattice is too restrictive. One of the search quality files (created when ***isqout*** = 1) is a raster grid highlighting any DEM cells that have a critical surface generated from a lattice node on the boundary of the search lattice (*<filein>_boundcheck_out.asc*). This file can be viewed in grid visualization software or a GIS. Ideally, all critical surfaces in areas of interest should be unrestricted by the extent of the search lattice (values in the boundary check file should equal 0). Non-zero values indicate which side of the lattice potentially restricted the search (table 4.7). Examples related to vertical boundary restrictions are shown in figure 5.8. If the search is restricted, then the user should expand the appropriate sides of the lattice for a more thorough search. The increased lattice extent will require additional computational effort and memory, but may be necessary for a thorough analysis. Note that cells near the edge of the DEM (in the buffer area) are not fully analyzed even when restrictions to the search lattice are eliminated. If the buffer area is important, then the extent of the DEM should be expanded.

Another output option (***icritlattice***) triggers the creation of a 3D search-lattice file (*<filein>_critfoslattice_out.3D*) highlighting the critical surfaces (section 4.5.3.4.1). Examining this file using 3D visualization software allows the user to determine whether any critical nodes in the lattice are on or near a lattice boundary. Critical nodes on a lattice boundary suggest that the user needs to expand the search lattice on that boundary. Ideally, all critical nodes for areas of interest in the DEM should have a few nodes not associated with a critical surface between them and the boundaries of the search lattice. If there are excessive null values near the lattice boundaries, the user may be able to trim the search lattice on those boundaries.

Figure 5.8. Images illustrating restrictions on the vertical extent of the search lattice for three different Scoops3D analyses. Examples are modifications of the Mount St. Helens example R (input file name: *R_sthel.scp*); see section 7.6. Left-side diagrams portray 3D critical search-lattice data (*<filein>_critfoslattice_out.3D*) above a perspective view of the DEM and right-side diagrams portray grid data from the search-lattice boundary check files (*<filein>_boundcheck_out.asc*) with 100 m contour lines. Boundary check values are assigned when critical surfaces are on the edge of the search lattice. *A*, Case where minimum elevation of the search lattice is too high (***zsmin*** is too large), as reflected in *boundcheck_out* values of 1 for important areas of the DEM. *B*, Case where maximum elevation of the search lattice is too low (***zsmax*** is too small), as reflected in *boundcheck_out* values of 9 for important areas of the DEM. *C*, Case where there are no search lattice boundary restrictions for important areas of the DEM (unmodified example *R_sthel.scp*). Note that some areas near the boundary of the DEM, deemed unimportant, may be restricted. Perspective images of *critfoslattice* files created using VisIt software and maps of *boundcheck* files created using Esri ArcMap software.



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5.3.6. Search Resolution

Search resolution is a major factor that controls the thoroughness of a Scoops3D search. We define search resolution to include the horizontal and vertical search-lattice node spacing, the radius increment for creating a sequence of spherical trial surfaces at a given node, and the number of potential slip directions analyzed for each trial surface. Ideally, adequate values for these parameters allow the creation of thousands or millions of trial surfaces encompassing all parts of the DEM. This, in turn, permits a thorough search for the minimum F at each DEM cell. With a higher resolution search (closely spaced lattice nodes, small radius increments, and multiple slip directions), Scoops3D will generate more tightly spaced trial surfaces and thus increase the chances of finding the trial surface with the minimum factor-of-safety for each DEM cell.

Increased search resolution increases computational effort and memory requirements. Thus, the user may want to adjust the resolution to provide results that are acceptable for a given project; for example, a preliminary, quick analysis may need only a coarse-resolution search whereas a more precise analysis may need a high-resolution search. Volumes associated with the critical potential failure masses may vary considerably when comparing results from high-resolution and low-resolution searches. For many searches, trial surfaces with similar factors of safety can lead to a large range in volumes (Reid and others, 2000). The user may need a high-resolution search to create map results with smoothly varying volumes or areas.

We have found that for our study cases, the coarse-to-fine search option (3.2.2) provides an adequate search; this option greatly reduces runtime and it is the default option in Scoops3D-i. The user will likely select this option for most analyses, except perhaps for cases in which memory limitations are more critical than computer runtime. For cases with very intricate topography and (or) strengths or pore pressures that vary greatly, the simple search option may be warranted to provide a thorough search. With both search options, search resolution involves four parameters: (1) the horizontal multiplier, (2) the vertical spacing, (3) the increment in the spherical radius, and (4) the number of slip directions analyzed for each trial surface. With the coarse-to-fine search option, the horizontal and vertical resolutions are for the fine lattice; the resolution of the coarse starting lattice is a multiple of the fine spacing. All these options can be adjusted from the Scoops3D-i **Search Configuration** window and are fully described in section 4.4.1.1.9.1. With the coarse-to-fine search, the coarse-to-fine multiplier (***multres***) will also affect runtime, but the optimal value is specific to the individual analysis. We found that a value of ***multres*** = 8 worked well for the study cases presented in chapters 6 and 7. If runtime optimization is desired, we recommend that the user compare runs, using a small, representative portion of the search lattice, with varied coarse-to-fine multipliers including values somewhat smaller (for example, 2 or 4) and larger (for example, 12 or 16) than the recommended values of 6 or 8 (section 3.2.2).

If computational speed and memory requirements are not a limitation, the user could, for example, define a high-resolution lattice, using a horizontal multiplier equal to 1 and vertical spacing equal to the DEM cell size, with a radius increment equal to half the cell size. With this high-resolution search, Scoops3D will likely find values near the ultimate minima, provided that the DEM resolution is appropriate for the size range of the trial failures (section 5.3.4).

If excessive runtime is an issue (as it may be with large, detailed analyses), then the user will need to reduce the lattice resolution even though this reduction may somewhat decrease the chances of finding the ultimate minima for each DEM cell. In this case, we suggest that the user start by using a relatively sparse spacing for the fine lattice (perhaps a horizontal multiplier of 4 and vertical spacing equal to 4 times the DEM cell size). By systematically performing Scoops3D analyses using progressively finer lattice resolutions, the user can compare factor-of-safety and size results with those from a high-resolution lattice and select a lattice resolution appropriate for the project (fig. 5.9). In addition, if the user wants more vertical resolution and is concerned about computational speed, we suggest decreasing the radius increment rather than increasing the vertical resolution. For each additional node in the search lattice, Scoops3D must first identify a potential failure mass near the minimum size criteria, which takes more computational effort than creating a potential failure mass in the appropriate size range with a new radius.

Examples of a trial-and-error approach with relatively low-, intermediate-, and high-resolution searches lattices are shown in figure 5.9. At first glance, the low-resolution results (fig. 5.9*F* and *G*; F_{min} =1.18) may seem adequate; however, the global minimum identified for the low-resolution search is 10 percent higher (fig. 5.9*H*) than the minimum for the high-resolution search (fig. 5.9*A* and *B*; F_{min} =1.07). Both the factor-of-safety and volume maps for the low-resolution search (fig. 5.9*F* and *G*) have irregular and splotchy transitions between the color bands; this is an indication of a lower quality search.

Although overall patterns of stability can be readily obtained with low-resolution searches, the poor quality of the search may lead to poor estimates of factor of safety and volume for specific potential failures. When a high-resolution search is not practical, a good compromise is an intermediate-resolution search (fig. 5.9*C* and *D*). When even the intermediate-resolution search requires excessive computer runtime, a low-resolution search can be used to compare scenarios (for example, different strengths or water conditions). The user can then refine the DEM resolution and search lattice extent as needed and perform a complete analysis with the intermediate-resolution search. The optimal search resolution to choose will depend on the user’s needs and may take some trial and error to obtain.

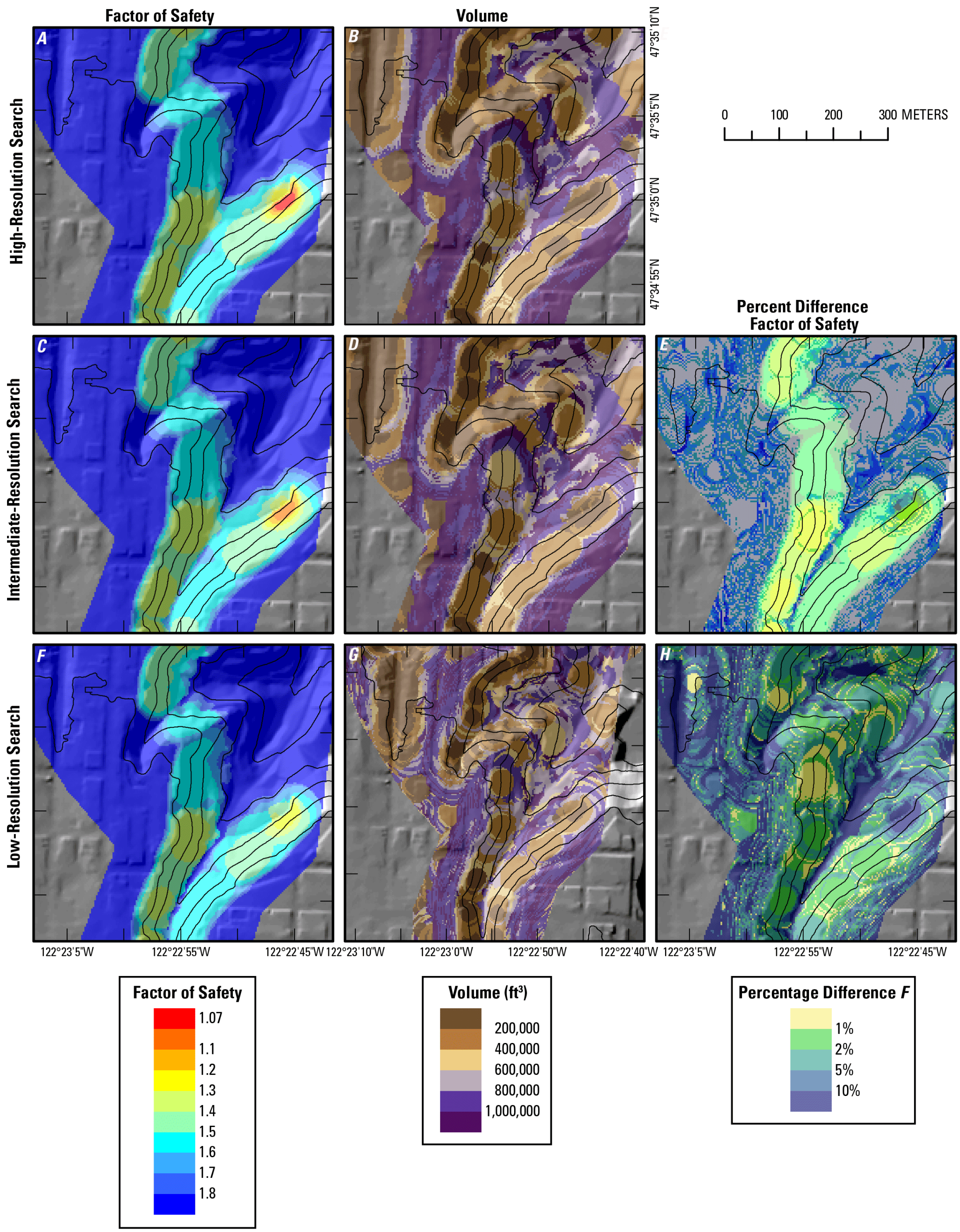

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Figure 5.9. Maps showing factor-of-safety and volume results from three Scoops3D analyses with three different search resolutions. Examples use variations of Seattle example Q (input file name: *Q_seawet.scp*); see section 7.5. Factors of safety from *<filein>_fos3d_out.asc* files and volumes from *<filein>_fosvol_out.asc* files. *A*, Factors of safety with high-resolution search, F_{min} = 1.07, V_{Fmin} = 3048 m^3. *B*, Critical volumes with high-resolution search. *C*, Factors of safety with intermediate-resolution search, F_{min} = 1.09, V_{Fmin} = 3239 m^3. *D*, Critical volumes with intermediate-resolution search. *E*, Percent difference in factors of safety for intermediate-resolution compared with high-resolution results. *F*, Factors of safety with low-resolution search, F_{min} = 1.18, V_{Fmin} = 3238 m^3. *G*, Critical volumes with low-resolution search. *H*, Percent difference in factors of safety, *F,* for low-resolution compared with high-resolution results. V_{Fmin} is critical volume. Percent difference in *F* is defined as (100*(F-$F_{highres}$)/$F_{highres}$). High-resolution search uses the parameters: horizontal multiplier, ***nsrchres*** = 1; vertical resolution, ***zsrchres*** = 10 ft; ***dr*** = 10 ft. Intermediate-resolution search uses the parameters: horizontal multiplier, ***nsrchres*** = 2; vertical resolution, ***zsrchres*** = 20 ft; ***dr*** = 10 ft. Low-resolution search uses the parameters: horizontal multiplier, ***nsrchres*** = 5; vertical resolution, ***zsrchres*** = 50 ft; ***dr*** = 10 ft. Details of the number of search-lattice nodes, number of trial surfaces, and computer runtime for the three search resolutions are shown in figure 5.1*A*. Maps created using Esri ArcMap software.

One additional component of search resolution is the number of slip directions analyzed for each trial surface. Scoops3D always analyzes trial surfaces with potential slip in the azimuthal direction of the overall fall direction. It is possible, however, that other slip directions may result in a minimum *F* for a given trial surface, especially in domains with complex topography and (or) spatially variable material properties and pore pressure conditions. The user can select options to analyze other slip directions as well (section 4.4.1.1.9.1) and compare the results with those from the overall fall direction analyses. Selecting other slip directions will slightly increase computer runtime but will not affect memory requirements.

5.3.7. Poor Solutions

Bishop's simplified method can sometimes converge to incorrect factor-of-safety values. Typically this occurs in only a few cases, particularly those in which the trial surface intersects the ground surface at a steep angle or where very high pore-fluid pressures act on the slip surface. For most problems, Bishop's simplified method will provide correct values. The method used in Scoops3D for computing an initial value of *F* helps prevent incorrect convergence (section 2.3.2). In some instances, however, the method will fail to converge to a solution and Scoops3D ignores these. In very rare situations, the method will converge but calculate a factor of safety that is too low, and these spurious low values end up being retained in the results from Scoops3D.

The user can detect these spurious values in two ways. (1) The factor-of-safety results from Bishop's simplified method can be compared with those from the Ordinary (Fellenius) method for the same critical surfaces (results from both are output when Bishop's simplified method is selected). When Bishop's method is functioning adequately, the solutions will be somewhat similar to each other (typically within ~50 percent). Note that the Ordinary method will always provide a solution to a given trial surface – the method is not subject to convergence issues. (2) The factor-of-safety results (in map view) from Bishop's simplified method can be examined for very localized low factors of safety. Spurious *F* values are commonly surrounded by much larger values; an example is shown in figure 5.10*A*.

Spuriously low factor-of-safety values typically occur when values of m_α (as defined in section 2.3.2) are close to zero. Thus, m_α can be used as a filter to remove poor Bishop's simplified values from the factor-of-safety results produced by Scoops3D. The ***absminma*** parameter in the Scoops3D main input parameter file (see section 4.4.1.1.8; Scoops3D-i option under **Options/Advanced Parameters**) controls this filter. Any trial surfaces with an absolute value of m_α less than ***absminma*** will be ignored in the search performed by Scoops3D. Typically, other valid trial surfaces will "fill in" any gaps in the analysis left by filtering these surfaces (fig. 5.10*B*).

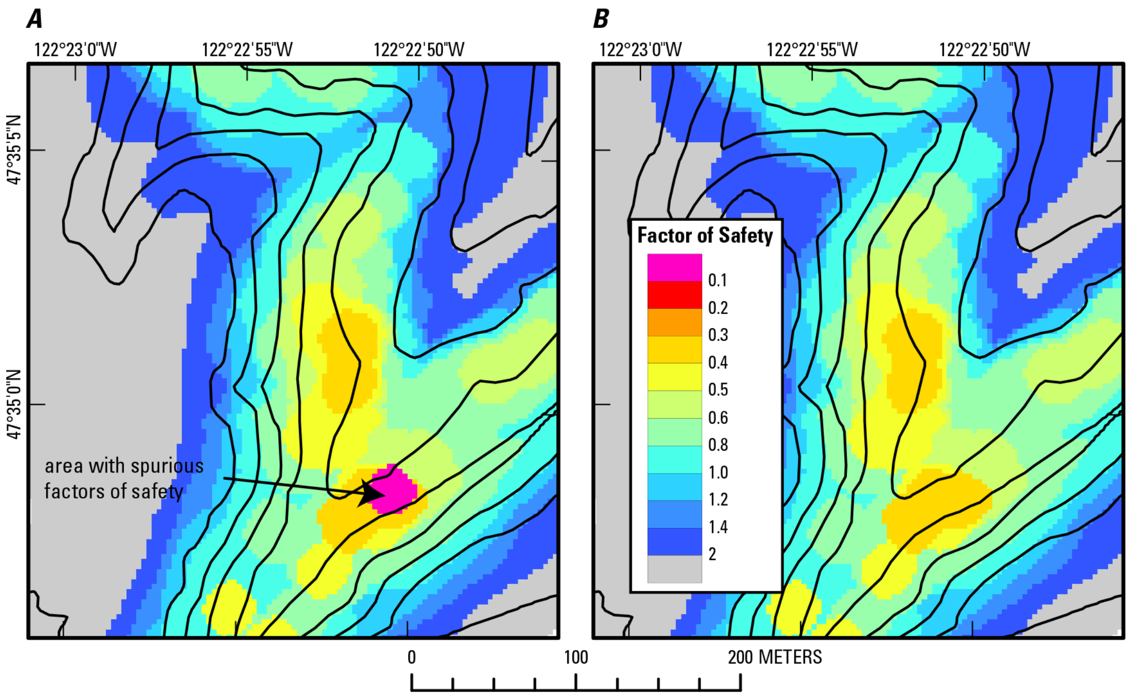


Figure 5.10. Maps showing results with spuriously low factors of safety and results with filtering. *A*, Areas with local spuriously low factors of safety obtained using Bishop's simplified method of analysis. *B*, Same areas after spurious values have been discarded using the m_α filter (***absminma*** = 0.05 in this case). DEM and strength values are from Seattle example Q (input file name: *Q_seawet.scp*) as described in section 7.5, with the addition of high pore-water pressures from scenario 3 of Brien and Reid (2007). Contour interval is 10 m. Maps created using Esri ArcMap software.

Selecting an appropriate m_α value for filtering, however, can entail some trial-and-error analysis. Setting this filter to a large value could unnecessarily exclude valid trial surfaces whereas setting it to a low value might allow poor results to be retained. Other researchers have set constant controls on m_α ranging from 0.001 to 0.00001 (for example Krahn, 2004; O. Hungr Geotechnical Research Inc., 2010). We have analyzed some problems in which a m_α filter of 0.05 eliminates clearly poor solutions without otherwise affecting the solution of critical surfaces. Scoops3D provides two output files that can be used to help assess the effects of a m_α filter. The filtered surfaces file (<*filein*>*_filter_out.txt*) lists all trial surfaces that either failed to converge or that were filtered (section 4.5.2.3). The filtered surfaces location file (<*filein*>*_filtergrid_out.asc*) is a raster grid showing the number of times surfaces were filtered or failed to converge at each DEM cell (section 4.5.2.4). An example map created from this file is shown in figure 5.11. The user can examine this file to determine whether excessive trial surfaces were filtered from areas of interest in the DEM.

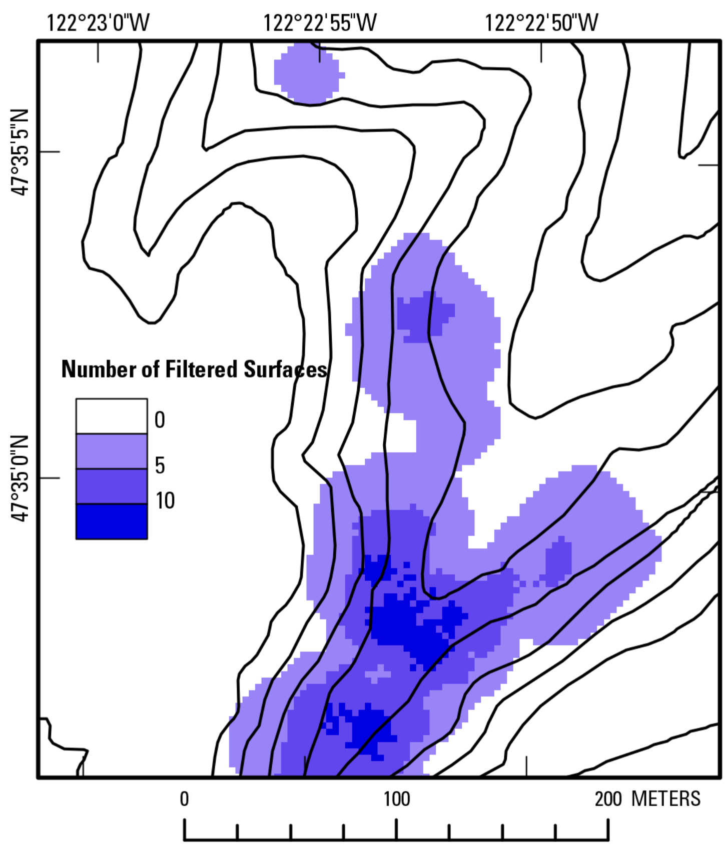


Figure 5.11. Map showing an example of number of filtered surfaces locations. Data contained in the <*filein*>*_filtergrid_out.asc* output file. Filtered surfaces either did not converge using Bishop's simplified method or were eliminated by the m_α filter. DEM and strength values are from Seattle example Q (input file name: *Q_seawet.scp*) described in section 7.5, with the addition of high pore pressures from scenario 3 of Brien and Reid (2007) (see also fig. 5.10). Contour interval is 10 m. Map created using Esri ArcMap software.

Chapter 6. Testing and Verification of Scoops3D

In this chapter, we present the results of verification tests using Scoops3D. Computer code verification is a demonstration of the ability of the software code to solve its governing equations correctly (Konikow and Bredehoeft, 1992) or essentially to evaluate whether the model performs as intended (Post and Votta, 2005). Our verification of Scoops3D includes comparison of the computed factor of safety, *F*, and volume for a given trial surface, and (or) the overall global critical surface with minimum *F*, with results from published 3D analytical solutions and other 2D and 3D slope-stability programs. When possible, we compare 3D solutions for both the Ordinary (Fellenius) and Bishop's simplified methods. Our testing consists of:

- Comparison with exact 3D analytical solutions for simple spherical trial surfaces with cohesion only.
- Comparison with 3D analytical solutions for log-spiral potential slip surfaces.
- Benchmark comparisons for 3D Bishop's simplified method with results from CLARA-W, a 3D slope stability program (O. Hungr Geotechnical Research Inc., 2010) for homogeneous, non-homogeneous, and piezometric surface scenarios. CLARA-W comparisons include examples taken from 3D analytical solutions and 3D extensions of commonly used 2D benchmark cases (for example, Arai and Tagyo, 1985; Donald and Giam, 1995).
- Benchmark comparisons of 2D examples using Scoops3D and CLARA-W, as well as other published results (Rocscience Inc., 2010; Feng and Fredlund, 2012).
- Demonstration of the equivalence of results computed using either raster grids or full 3D material property and pressure-head files.
- Assessment of the minimum number of active columns required for accurate estimation of potential failure volume and factor of safety.
- Symmetry tests to demonstrate the ability of Scoops3D to compute factors of safety for potential failure masses with slip directions not aligned with the DEM coordinate axes.
- Assessment of Scoops3D's ability to incorporate the effects of unsaturated suction stresses.

We evaluated differences in factor of safety, *F*, and potential failure volume, *V*, computed with Scoops3D against other solutions for a given benchmark example using:

$$\%\,difference\;F = \left(\frac{F_{SCOOPS} - F_{Benchmark}}{F_{Benchmark}}\right)100 \text{, and} \tag{6.1}$$

$$\%\,difference\;V = \left(\frac{V_{SCOOPS} - V_{Benchmark}}{V_{Benchmark}}\right)100\text{,} \tag{6.2}$$

where

F_{SCOOPS}	is the factor of safety computed by Scoops3D,
$F_{Benchmark}$	is the factor of safety computed by other slope-stability software or analytical solutions,
V_{SCOOPS}	is the volume computed by Scoops3D, and
$V_{Benchmark}$	is the volume computed by other slope-stability software or analytical solutions.

Although it is difficult to evaluate all possible combinations of options available in Scoops3D, we chose a wide variety of verification examples, including analysis of the stability of homogeneous straight and curved slopes, layered slopes, and slopes subjected to earthquake loading and pore-water pressures. Table 6.1 summarizes our examples and comparison methods. We provide input and output files for selected verification examples in the Scoops3D *examples* folder, as discussed in chapter 7.

Table 6.1. Summary of verification examples, limit-equilibrium methods, parameters tested, and references for comparison solutions.

['O' indicates Ordinary (Fellenius) method, 'B' indicates Bishop's simplified method, c is material cohesion, ϕ is material angle of internal friction, r_u is pore-pressure ratio, and eq is horizontal pseudo-acceleration coefficient from earthquake loading]

Sections	Description	Method	Material strength (c and ϕ)	Additional parameters	Reference	Scoops3D comparison with			
						Analytical 3D	CLARA-W 3D	CLARA-W 2D	Published 2D
6.1, 6.3.1	Uniform slope	O, B	Homogeneous, c only		Gens and others (1988)	x	x	x	
6.2.1, 6.3.1, 6.4.1	Homogeneous embankment	O, B	Homogeneous, c and ϕ		Leshchinsky and others (1985)	x	x	x	
6.4.1	Wet homogeneous embankment	B	Homogeneous, c and ϕ	r_u				x	
6.2.2, 6.3.1	Homogeneous cones	O, B	Homogeneous, c and ϕ		Baker and Leshchinsky (1987)	x	x	x	
6.2.3, 6.3.1	Wet homogeneous cones	O, B	Homogeneous, c and ϕ	r_u	Leshchinsky and Mullet (1987)	x	x	x	
6.3.2, 6.4.1, 6.4.2	Embankment	B	Homogeneous and non-homogeneous	eq	3D extension of Donald and Giam 1995)		x	x	x
6.3.3, 6.4.1, 6.4.2	Embankment	B	Homogeneous and non-homogeneous	Piezometric surface	3D extension of Arai and Tagyo 1985)		x	x	x

6.1. Comparison with Exact 3D Analytical Solutions

There are many published examples with analytical solutions for slope stability, but very few examples for a 3D spherical trial surface. We chose an example for a uniform slope with a purely cohesive, homogeneous, isotropic soil (Gens and others, 1988) that was also used by Hungr and others (1989) to verify the CLARA-W software. We compared Scoops3D results with the 3D analytical solution for a spherical slip surface on a 2:1 straight slope (26.6°) (fig. 6.1) with the following parameters, where the solution for *F* is not dependent on a particular system of units:

R = 1	is the radius of the sphere (L),
z = 0.5	is the perpendicular distance from center of sphere to ground surface (L),
c = 0.1	is cohesion ($ML^{-1}T^{-2}$),
γ = 1.0	is unit weight ($ML^{-2}T^{-2}$), and
ϕ = 0.0	is angle of internal friction.

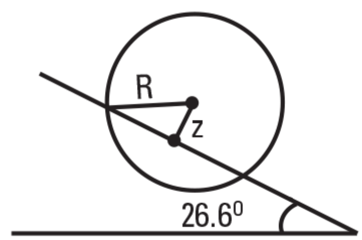


Figure 6.1. Schematic diagram showing 2D cross section through the slope and trial surface used in the purely cohesive example. Example analyzed is a 3D version of a 2:1 (26.6°) straight, uniform slope.

The 3D analytical solution for factor of safety is *F* = 1.402 (Hungr and others, 1989; Michalowski and Drescher, 2009). The slip surface volume can be computed using the volume equation for a spherical cap, yielding a value of 0.654 cubic length units. Note that this trial surface is not the critical surface for the slope; we use this for consistency with other publications.

The factors of safety, *F*, computed using both the Ordinary and Bishop's simplified methods in Scoops3D are within 0.14 percent of the 3D analytical solution (table 6.2). Scoops3D estimates a volume of 0.655 cubic length units; this is 0.15 percent greater than the volume of a comparable spherical cap.

Table 6.2. Comparison of computed 3D factor of safety, *F*, from Scoops3D with the 3D analytical solution for the purely cohesive example.

[The Scoops3D potential failure mass contains 150,292 columns]

Analytical solution	Scoops3D		Percent difference from analytical solution	
3D *F*	*F*_Bishop	*F*_Ordinary	*F*_Bishop	*F*_Ordinary
1.402	1.400	1.400	-0.14	-0.14

6.2. Comparison with 3D Analytical Solutions for Log-Spiral Slip Surfaces

To our knowledge, there are no published 3D analytical solutions for spherical trial surfaces with soils having both cohesive and frictional strength. There are, however, some 3D analytical chart solutions that use variational principles to obtain minimum *F* values for log-spiral shaped potential slip surfaces in generic cones (Baker and Leshchinsky, 1987; Leshchinsky and Mullett, 1987) and embankments (Leshchinsky and others, 1985). We compared results from Scoops3D with these 3D analytical solutions. Because the slip surfaces are logarithmic spirals rather than spheres, we do not expect Scoops3D to perfectly match the analytical solutions. Nevertheless, the analytical solutions cover a wide range of slope angles and strength values and are useful for assessing whether Scoops3D provides reasonable results in a variety of circumstances. We compared dry, homogeneous embankment examples and homogeneous cone examples under both dry and wet conditions, specified by the pore-pressure ratio, r_u.

For comparison with the 3D analytical solutions, we performed extensive searches using Scoops3D to identify the potential failure masses with the global minimum *F* computed with both the Ordinary and Bishop's simplified methods. For dry cones, we also compared the volume of the potential failure mass having the global minimum *F* identified by Scoops3D with the volume of the log-spiral surface related to the 3D analytical solution. Analytical solutions for the volume of the global minimum *F* with wet cones were not available for comparison.

6.2.1. Homogeneous, Dry Embankments with 3D Analytical Solutions for Log-Spiral Slip Surfaces

We compared Scoops3D results with Leshchinsky and others (1985) 3D analytical solutions for log-spiral shaped potential slip surfaces in dry embankments with 30° and 60° slopes and a range of *c* and ϕ values (table 6.3). We used embankments with a height, *H*, of 10 m and material properties that covered a wide range of ratios of cohesive to frictional strengths (table 6.3), as characterized by the dimensionless ratio λ, (equation 5.1)

Table 6.4 compares Scoops3D results with the 3D analytical solutions for dry embankments. In all cases, factors of safety calculated by Scoops3D for both the Ordinary and Bishop's simplified methods are lower than the analytical solutions due to differences in the shape of the trial surfaces; however, all of the analytical solutions are within ~9 percent of Scoops3D Bishop's method results and within ~11 percent of the Ordinary method results. In section 6.3.1, we compare 3D results from Scoops3D and the CLARA-W software using spherical trial surfaces for these same 30º and 60º dry embankments.

Table 6.3. List of material properties and calculated λ values for the dry embankment comparison tests.

[The embankment has height, *H* = 10 m. Parameters for materials: *c* is cohesion, ϕ is angle of internal friction, and γ_t is total unit weight. º, degree; kN, kilonewton; kPa, kilopascal; m, meter]

λ	γ_t (kN/m^3)	ϕ (°)	*c* (kPa)
1.00	20	30	116.
0.125	19	20	8.64
0.025	17	10	0.75

Table 6.4. Comparison of Scoops3D factor-of-safety results with 3D analytical chart solutions for dry embankments, given different values of λ.

[Analytical solutions are from Leshchinsky and others (1985) charts for log-spiral slip surfaces. Solutions in Scoops3D are for the spherical trial surface with the global minimum *F* using either Bishop's simplified method or the Ordinary method. Note that the critical potential failure masses (global minimum) are slightly different for the Ordinary and Bishop's simplified methods, thus the volumes differ]

[º, degree; m, meter]

λ	Slope (°)	Chart solution (Leshchinsky and others, 1985)	Scoops3D Global minimum using Bishop's method		Scoops3D Global minimum using Ordinary method		Percent difference from chart solution	
		3D *F*	*F*_Bishop	Volume (m^3)	*F*_Ordinary	Volume (m^3)	*F*_Bishop	*F*_Ordinary
1.00	60	5.19	4.72	582	4.88	729	-9.0	-6.1
0.125	60	0.80	0.75	326	0.75	341	-6.4	-6.7
0.025	60	0.20	0.19	163	0.19	152	-3.7	-6.6
1.00	30	6.83	6.38	4,489	6.14	5,407	-6.6	-10.1
0.125	30	1.41	1.32	1,157	1.26	1,286	-6.4	-10.8
0.025	30	0.42	0.41	522	0.40	555	-1.3	-4.5

6.2.2. Homogeneous, Dry Cones with 3D Analytical Solutions for Log-Spiral Slip Surfaces

We also compared Scoops3D results with Baker and Leshchinsky's (1987) 3D analytical solution for logarithmic spiral potential slip surfaces in dry cones with a height, H = 1000 m, three different slope angles, and a range of c and ϕ values. The material properties cover a wide range of λ values (table 6.5). We compared Scoops3D factor of safety and volume of the global minimum spherical trial surface for each combination of slope angle and λ to the 3D analytical solution for logarithmic spiral slip surfaces with dry conditions (table 6.6). Input files for the 30° cone example are provided in the Scoops3D *examples* folder (Scoops3D examples K through O, section 7.4).

Scoops3D solutions for the factor of safety, F, using Bishop's simplified method are within ~1 to 2 percent of Baker and Leshchinsky's (1987) solutions (table 6.6), with the largest difference correlating with the largest discrepancy in volume. The Ordinary solution underestimates F in all cases, typically by a few percent but by as much as ~6 percent in one case. Computed volumes for the Scoops3D spherical trial surface with the global minimum F are typically within 9 percent of the volumes for Baker and Leshchinsky's log spiral slip surfaces, but differences are as large as ~28 percent for a 30° slope with low λ. Large differences in volume can arise from the shape differences between the Scoops3D spherical surfaces and the analytical solution logarithmic spirals; thus some difference in results should be expected.

Table 6.5. List of material properties and calculated λ values used in the dry cone comparison tests.

[The cones have height, H = 1000 m. Parameters for materials: c is cohesion, ϕ is angle of internal friction, and γ_t is total unit weight. °, degree; kN, kilonewton; kPa, kilopascal; m, meter]

λ	γ_t ((kN/m^3)	ϕ (°)	c (kPa)
1.00	21	40	17,630
0.125	20	30	1,444
0.0625	19	25	553.8
0.025	19	20	172.9

Table 6.6. Comparison of Scoops3D factor-of-safety and volume results with 3D analytical chart solutions for dry, homogeneous cones, given different values of λ.

[Analytical solutions are from Baker and Leshchinsky's (1987) charts for log-spiral slip surfaces. Scoops3D solutions are for a spherical trial surface with the global minimum factor of safety (*F)* using either Bishop's simplified method or the Ordinary method. Note that the critical potential failure masses (global minimum) are slightly different for the Ordinary and Bishop's simplified methods, thus the volumes (*V*) may differ. º, degree; m, meter]

λ	Slope (°)	Chart solution (Baker and Leshchinsky, 1985)		Scoops3D Global minimum using Bishop's method		Scoops3D Global minimum using Ordinary method		Percent difference from chart solution		
		3D *F*	Volume (m^3)	*F*_Bishop	Volume (m^3)	*F*_Ordinary	Volume (m^3)	*F*_Bishop	*F*_Ordinary	*V*_Bishop
1.00	70	7.596	6.6728×10^7	7.595	6.5951×10^7	7.590	6.5951×10^7	-0.01	-0.08	-1.16
0.125	70	1.155	4.4670×10^7	1.156	4.4615×10^7	1.144	4.5547×10^7	0.09	-0.95	-0.12
0.0625	70	0.651	3.5098×10^7	0.651	3.4986×10^7	0.639	3.5968×10^7	0.00	-1.84	-0.32
1.00	50	9.326	2.4774×10^8	9.231	2.5601×10^8	9.155	2.6215×10^8	-1.02	-1.83	3.34
0.125	50	1.564	1.4525×10^8	1.567	1.4584×10^8	1.516	1.5030×10^8	0.19	-3.07	0.40
0.025	50	0.533	7.0783×10^7	0.536	6.4447×10^7	0.516	7.4994×10^7	0.56	-3.19	-8.95
1.00	30	11.259	1.1561×10^9	11.200	1.3002×10^9	10.864	1.4034×10^9	-0.52	-3.50	12.47
0.125	30	2.329	5.1208×10^8	2.300	5.4531×10^8	2.190	6.2039×10^8	-1.25	-5.97	6.49
0.025	30	0.889	1.9478×108	0.907	2.5012×108	0.878	2.8446×108	2.02	-1.24	28.41

6.2.3. Homogeneous, Wet Cones with 3D Analytical Solutions for Log-Spiral Slip Surfaces

We added pore-pressure effects to the cone examples presented in the previous section and compared Scoops3D results with Leshchinsky and Mullett's (1987) 3D analytical solution for wet cones. Again, the analytical solutions are for potential slip surfaces with the shape of logarithmic spirals. We used the same cone specifications and λ values shown in table 6.5. Pore-pressure effects were specified by the pore-pressure ratio, r_u. We compared results from each combination of slope angle and λ value for two pore-pressure ratios: $r_u = 0.1$ and $r_u = 0.4$ (a relatively high value) in table 6.7.

Scoops3D solutions for factor of safety, *F*, using Bishop's simplified method are all within ~2 percent of the 3D analytical chart solutions (table 6.7). For steeper cones and (or) high pore pressures, the Ordinary method overestimates *F* by as much as 9 percent. Again, some differences should be expected, as the shape differs between log-spiral slip and spherical trial surfaces.

Table 6.7. Comparison of Scoops3D factor-of-safety and volume results with 3D analytical chart solutions for wet, homogeneous cones, given different values of λ.

[Analytical solutions are from Leshchinsky and Mullett's (1987) charts for log-spiral slip surfaces. Scoops3D solutions are for the spherical trial surface with the global minimum *F* using either Bishop's simplified method or the Ordinary method. Note that the critical potential failure masses (global minimum) are slightly different for the Ordinary and Bishop's simplified methods, thus the volumes may differ slightly. The parameter r_u is pore-pressure ratio. °, degree; m, meter]

λ	r_u	Slope (°)	Chart solution (Leshchinsky and Mullett, 1987)	Scoops3D Global minimum using Bishop's method		Scoops3D Global minimum using Ordinary method		Percent difference from chart solution	
			3D *F*	*F*_Bishop	Volume (m³)	*F*_Ordinary	Volume (m³)	*F*_Bishop	*F*_Ordinary
1.00	0.1	70	7.390	7.416	6.5951×10^{7}	7.411	6.5951×10^{7}	0.35	0.28
1.00	0.4	70	6.888	6.875	6.5825×10^{7}	6.890	6.6593×10^{7}	-0.19	0.03
0.125	0.1	70	1.036	1.032	4.3538×10^{7}	1.019	4.5115×10^{7}	-0.39	-1.64
0.125	0.4	70	0.669	0.652	4.0575×10^{7}	0.711	4.8483×10^{7}	-2.54	6.28
0.0625	0.1	70	0.550	0.551	3.2612×10^{7}	0.533	3.5968×10^{7}	0.18	-3.09
0.0625	0.4	70		Most surfaces did not converge		0.308	4.0171×10^{7}	---	---
1.00	0.1	50	8.996	9.014	2.5601×10^{8}	8.936	2.6883×10^{8}	0.20	-0.67
1.00	0.4	50	8.334	8.352	2.6928×10^{8}	8.308	2.7467×10^{8}	0.22	-0.31
0.125	0.1	50	1.435	1.439	1.4584×10^{8}	1.382	1.6000×10^{8}	0.28	-3.69
0.125	0.4	50	1.064	1.053	1.5448×10^{8}	1.021	1.7642×10^{8}	-1.03	-4.04
0.025	0.1	50	0.462	0.461	6.8255×10^{7}	0.436	7.8454×10^{7}	-0.22	-5.63
0.025	0.4	50	0.243	0.238	6.7243×10^{7}	0.231	8.5218×10^{7}	-2.06	-4.94
1.00	0.1	30	10.913	10.886	1.3468×10^{9}	10.536	1.4510×10^{9}	-0.25	-3.45
1.00	0.4	30	10.049	9.914	1.4595×10^{9}	9.564	1.6831×10^{9}	-1.34	-4.83
0.125	0.1	30	2.134	2.133	5.7374×10^{8}	2.013	6.5433×10^{8}	-0.05	-5.67
0.125	0.4	30	1.644	1.626	6.6610×10^{8}	1.480	8.2440×10^{8}	-1.09	-9.98
0.025	0.1	30	0.812	0.815	2.5012×10^{8}	0.782	3.0526×10^{8}	0.37	-3.69
0.025	0.4	30	0.536	0.536	2.9151×10^{8}	0.488	3.9167×10^{8}	0.00	-8.96

6.3. Comparison with CLARA-W 3D Benchmark Solutions

We benchmarked solutions from Scoops3D against those from CLARA-W, a 2D and 3D slope-stability program (O. Hungr Geotechnical Research Inc., 2010) that is capable of using spherical trial surfaces that exactly match Scoops3D trial surfaces. CLARA-W does not have an option for the Ordinary method; therefore, we compared 3D solutions using only Bishop's simplified method. In our comparisons, we first performed an extensive search in Scoops3D to identify the trial surface with the global minimum *F* using Bishop's simplified method. We then used the rotational center and radius of that global minimum trial surface to define the same spherical trial surface in CLARA-W. Note that CLARA-W permits slip rotation in only one direction, which must be aligned with the DEM grid axes; therefore, we aligned the grids appropriately for the comparisons. We compared the factor of safety and volume for identical surfaces computed by each program.

We compared Scoops3D and CLARA-W results for a variety of cases, including the 3D analytical examples of homogeneous embankments and cones described in section 6.2. We supplemented these examples with an additional, more gently sloping, 10° embankment, an example that does not have a chart solution in Baker and Leshchinsky (1987). To test additional features of Scoops3D, we examined embankment examples commonly used for verification of 2D factor of safety calculations (Arai and Tagyo, 1985; Donald and Giam, 1995; Rocscience Inc., 2010; Feng and Fredlund, 2012) that we extended into 3D for comparison with CLARA-W results. These additional tests assessed the effects of earthquake loading, non-homogeneous material properties defined by layers, and a piezometric surface describing the subsurface pore-pressure distribution.

6.3.1. Homogeneous Slopes Analogous to 3D Analytical Solutions

Using the examples described in section 6.2, we compared the volumes and 3D factors of safety computed by Bishop's simplified method in Scoops3D with results from CLARA-W for homogeneous slopes, including a uniform slope with dry, purely cohesive soil, dry embankments, and dry and wet cones (table 6.8). For each case, both programs used identical spherical trial surfaces. Because CLARA-W provides *F* results to only two decimal places, we use this precision to calculate the differences. The 3D results on identical trial surfaces using the two software packages, Scoops3D and CLARA-W, provide factors of safety and volumes that differ by at most ~1 percent for all of our test cases; most examples have a discrepancy of 0.01 percent or less (table 6.8).

Table 6.8. Comparison of Scoops3D and CLARA-W results for homogeneous uniform slopes, embankments, and cones, given different values of λ.

[Bishop's 3D factors of safety (*F*) and volumes (*V*) are for the global minimum spherical trial surface identified by Scoops3D. Factors of safety for the more rigorous Spencer method, computed by CLARA-W, are also shown. The designation "No conv." means the solution for *F* did not converge in this case; the parameter r_u is pore-pressure ratio. °, degree; m, meter; λ, lambda]

λ	r_u	Slope (°)	Scoops3D		CLARA-W 3D			Comparison with CLARA-W	
			*F*_Bishop	Volume (m^3)	*F*_Bishop	*F*_Spencer	Volume (m^3)	Percent difference *F*	Percent difference *V*
Straight, uniform slope									
∞	0	26.6	1.40	0.655	1.40	No conv.	0.65	0.0	0.77
Homogeneous embankments									
1.00	0	60	4.73	547.3	4.72	No conv.	547.2	0.2	0.03
0.125	0	60	0.75	335.3	0.75	0.76	334.6	0.0	0.20
0.025	0	60	0.19	153.3	0.19	No conv.	153.4	0.0	-0.06
1.00	0	30	6.38	4,576	6.38	6.38	4578	0.0	-0.05
0.125	0	30	1.32	1,124	1.32	1.32	1123	0.0	0.05
0.025	0	30	0.41	526.9	0.41	0.41	528.6	0.0	-0.33
1.00	0	10	10.07	5.69639×10^4	10.07	10.07	5.68980×10^4	0.0	0.12
0.125	0	10	3.01	1.65894×10^4	3.01	No conv.	1.65960×10^4	0.0	-0.04
0.025	0	10	1.15	7953	1.15	1.15	7949	0.0	0.04
Homogeneous cones									
1.00	0	70	7.60	6.59505×10^7	7.59	No conv.	6.59503×10^7	0.1	0.00
0.125	0	70	1.16	4.46153×10^7	1.15	No conv.	4.46134×10^7	0.9	0.00
0.0625	0	70	0.65	3.47357×10^7	0.65	0.65	3.47328×10^7	0.0	0.01
1.00	0.1	70	7.42	6.59505×10^7	7.41	No conv.	6.59503×10^7	0.1	0.00
0.125	0.1	70	1.03	4.35381×10^7	1.03	No conv.	4.35403×10^7	0.0	-0.01
0.0625	0.1	70	0.55	3.46348×10^7	0.55	0.55	3.46343×10^7	0.0	0.00

λ	r_u	Slope (°)	Scoops3D		CLARA-W 3D			Comparison with CLARA-W	
			*F*_Bishop	Volume (m^3)	*F*_Bishop	*F*_Spencer	Volume (m^3)	Percent difference *F*	Percent difference *V*
Homogeneous cones—Continued									
1.00	0.4	70	6.88	6.58248×10^7	6.88	No conv.	6.58253×10^7	0.0	0.00
0.125	0.4	70	0.68	5.00932×10^7	0.68	0.67	5.00932×10^7	0.0	0.00
1.00	0	50	9.23	2.56006×10^8	9.22	No conv.	2.56021×10^8	0.1	-0.01
0.125	0	50	1.57	1.45837×10^8	1.57	1.55	1.45849×10^8	0.0	-0.01
0.025	0	50	0.54	6.44472×10^7	0.54	0.53	6.44540×10^7	0.0	-0.01
1.00	0.1	50	9.01	2.56006×10^8	9.00	No conv.	2.56021×10^8	0.1	-0.01
0.125	0.1	50	1.44	1.45837×10^8	1.44	1.43	1.45849×10^8	0.0	-0.01
0.025	0.1	50	0.46	6.82550×10^7	0.46	0.46	6.82627×10^7	0.0	-0.01
1.00	0.4	50	8.35	2.69278×10^8	8.34	No conv.	2.69288×10^8	0.1	0.00
0.125	0.4	50	1.05	1.54475×10^8	1.05	1.03	1.54488×10^8	0.0	-0.01
0.025	0.4	50	0.28	1.38057×10^8	0.28	0.29	1.38066×10^8	0.0	-0.01
1.00	0	30	11.20	1.30024×10^9	11.21	11.19	1.30041×10^9	-0.1	-0.01
0.125	0	30	2.30	5.45313×10^8	2.30	2.29	5.45373×10^8	0.0	-0.01
0.025	0	30	0.91	2.50123×10^8	0.91	0.90	2.50143×10^8	0.0	-0.01
1.00	0.1	30	10.89	1.30024×10^9	10.90	10.88	1.30041×10^9	-0.1	-0.01
0.125	0.1	30	2.13	5.73742×10^8	2.13	2.12	5.73809×10^8	0.0	-0.01
0.025	0.1	30	0.82	2.50123×10^8	0.82	0.81	2.50143×10^8	0.0	-0.01
1.00	0.4	30	9.91	1.45968×10^9	9.93	10.74	1.45985×10^9	-0.2	-0.01
0.125	0.4	30	1.63	6.66101×10^8	1.63	1.62	6.66178×10^8	0.0	-0.01
0.025	0.4	30	0.54	2.91509×10^8	0.54	0.54	2.91562×10^8	0.0	-0.02

6.3.2. Additional Embankment Examples – Homogeneous Properties, Non-Homogeneous Properties, and Earthquake Loading

Donald and Giam (1995) developed a set of example problems that are commonly used for verification of 2D slope-stability software (Rocscience Inc., 2010; Feng and Fredlund, 2012). We extended these examples to represent spherical trial surfaces in 3D embankments, and included cases with earthquake loading and non-homogeneous material properties defined by layers. We compared Scoops3D and CLARA-W 3D results for each example using identical spherical trial surfaces encompassing at least 1,847 active columns. Three cases (Donald and Giam's [1995] examples 1a, 1c, and 1d) are described below and comparison results are shown in table 6.11. Input files for these examples are provided in the Scoops3D *examples* folder (Scoops3D examples F through J, section 7.3). Note that in section 6.4, we also use Scoops3D to compute 2D solutions for comparison with the 2D solutions of these benchmark tests.

The first case (1a in Donald and Giam [1995]) consists of a 10 m tall homogeneous embankment with a 2:1 slope (~26.6°) and the material properties shown in table 6.9.

Table 6.9. List of material properties and calculated λ value for the 2:1 slope, homogeneous embankment example.

[Embankment has height, H = 10 m. From example 1a in Donald and Giam (1995). Parameters for materials: c is cohesion, ϕ is angle of internal friction, and γ_t is total unit weight. °, degree; kN, kilonewton; kPa, kilopascal; m, meter]

λ	γ_t (kN/m^3)	ϕ (°)	c (kPa)
0.04	20	19.6	3

The second case (1c in Donald and Giam [1995]) has the same ground surface configuration as the simple homogeneous embankment, with the addition of three soil layers, each having different material properties (fig. 6.2). The material properties are listed in table 6.10 and our 3D extension of the example is shown in figure 6.3.

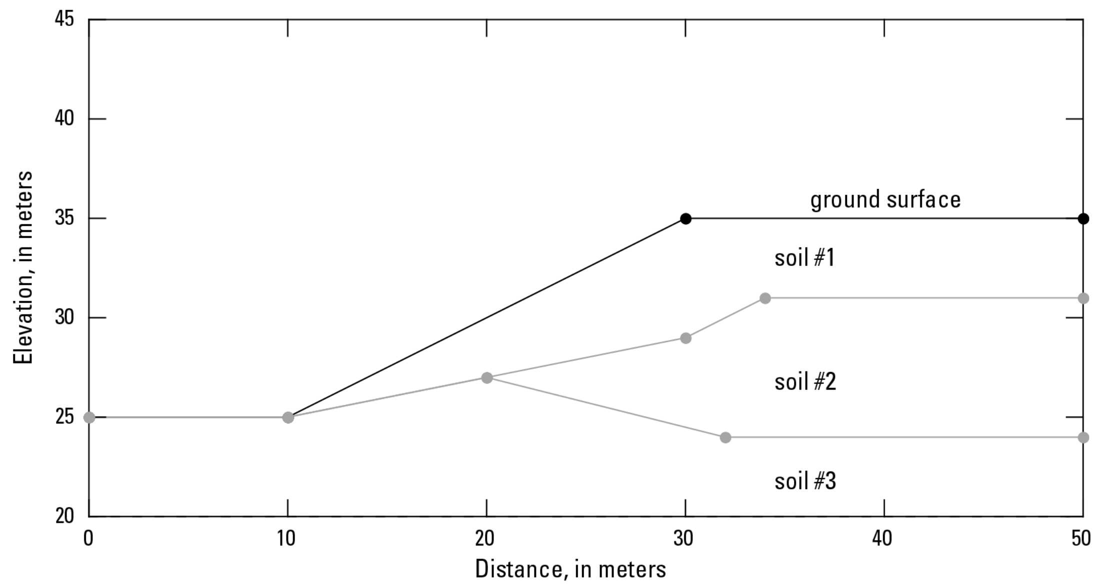


Figure 6.2. 2D cross section through the soil layers in the 2:1 slope, non-homogeneous embankment example. The embankment has height, *H* = 10 m. From example 1c in Donald and Giam (1995).

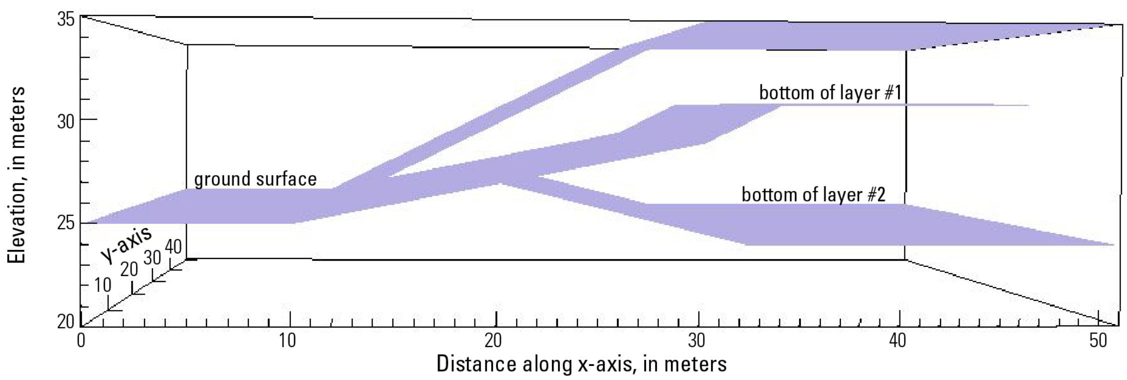


Figure 6.3. A 3D perspective view of soil layers in the 2:1 slope, non-homogeneous 3D embankment example. This represents a 3D extension of example 1c in Donald and Giam (1995).

Our third example (1d in Donald and Giam [1995]) is identical to the layered embankment described above (table 6.10 and fig. 6.3) with the addition of earthquake loading, defined as a horizontal seismic pseudo-acceleration coefficient (***eq***) of 0.15 oriented in the direction of slip.

We compare the 3D factors of safety computed using Bishop's simplified method in Scoops3D and CLARA-W for the three Donald and Giam (1995) embankment examples in table 6.11. Because CLARA-W provides only two decimal places for factor of safety, we use this precision for computation of the percent difference in *F*. Given this level of precision, there is no difference between the two software packages for these three cases (table 6.11).

Table 6.10. List of material properties and calculated λ values for the 2:1 slope, non-homogeneous 3D embankment example.

[Taken from example 1c in Donald and Giam (1995). Parameters for materials: *c* is cohesion, ϕ is angle of internal friction, and γ_t is total unit weight. °, degree; kN, kilonewton; kPa, kilopascal; m, meter]

Soil layer	λ	γ_t (kN/m³)	ϕ (°)	*c* (kPa)
1	0	19.5	38	0
2	0.06	19.5	23	5.3
3	0.10	19.5	20	7.2

Table 6.11. Comparison of Scoops3D and CLARA-W results for the 2:1 slope, homogeneous and non-homogeneous 3D embankment examples.

[Factors of safety (*F*) computed using 3D Bishop's simplified method. Embankments are 3D extensions of Donald and Giam's (1995) examples for a homogeneous embankment (1a), non-homogeneous embankment (1c), and non-homogeneous embankment with earthquake loading, ***eq*** (1d)]

Donald and Giam's (1995) example #	Material properties	*eq*	Scoops3D *F*	CLARA-W *F*	Percent difference from CLARA-W
1a	Homogeneous	0	1.04	1.04	0.0
1c	Non-homogeneous	0	1.51	1.51	0.0
1d	Non-homogeneous	0.15	1.09	1.09	0.0

6.3.3. Additional Embankment Examples - Homogeneous Properties, Non-Homogeneous Properties, and Piezometric Surface

Arai and Tagyo (1985) also developed a set of example problems that are commonly used for verification of 2D slope stability software (Rocscience Inc., 2010; Feng and Fredlund, 2012). This set of examples includes material properties with higher cohesive strength than the Donald and Giam (1995) embankment configuration (section 6.3.2) and the addition of a piezometric surface. We extended these examples into 3D and used identical spherical trial surfaces, containing at least 6454 active columns, to compare Scoops3D and CLARA-W results. Input files for these examples are provided in the Scoops3D *examples* folder (Scoops3D examples A through E, section 7.2). Note that in section 6.4, we also compare 2D solutions computed in Scoops3D with the 2D benchmark solutions from Arai and Tagyo (1985).

The first Arai and Tagyo (1985) example (1) consists of a 20 m tall homogeneous embankment with a 3:2 slope (~33.7°) and the material properties shown in table 6.12.

Table 6.12. List of material properties and calculated λ value for the 3:2 slope, homogeneous embankment example.

[The embankment height, H = 20 m. Example 1 in Arai and Tagyo (1985). Parameters for materials: c is cohesion, ϕ is angle of internal friction, and γ_t is total unit weight. °, degree; kN, kilonewton; kPa, kilopascal; m, meter]

λ	γ_t (kN/m³)	ϕ (°)	c (kPa)
0.41	18.82	15	41.65

The second example (2) has the same configuration as that defined for the simple homogeneous embankment example (1), but with the addition of three layers, each having different material properties (fig. 6.4). The material properties are shown in table 6.13 and our 3D extension of the example is shown in figure 6.5.

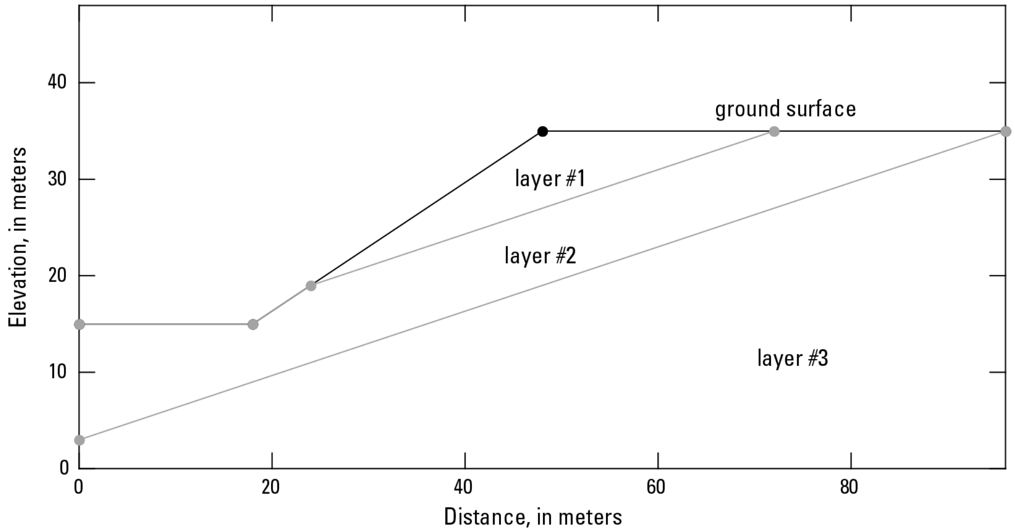


Figure 6.4. 2D cross section of soil layers for the 3:2 slope, non-homogeneous embankment example. Embankment height, H = 20 m. Example 2 in Arai and Tagyo (1985).

Table 6.13. List of material properties and calculated λ values for the 3:2 slope, non-homogeneous embankment example.

[Embankment height, H = 20 m. Example 2 in Arai and Tagyo (1985). Parameters for materials: c is cohesion, ϕ is angle of internal friction, γ_{ps} is partially saturated unit weight, γ_s is saturated unit weight, and γ_t is total unit weight. °, degree; kN, kilonewton; kPa, kilopascal; m, meter]

Layer	λ	$\gamma_t = \gamma_{ps} = \gamma_s$ (kN/m³)	ϕ (°)	c (kPa)
1	0.37	18.82	12	29.4
2	0.30	18.82	5	9.8
3	0.93	18.82	40	294

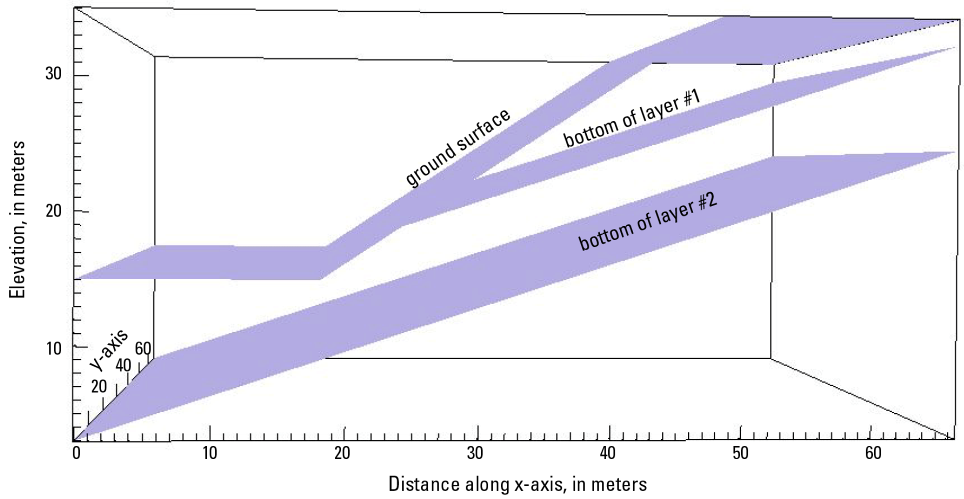


Figure 6.5. A 3D perspective view of soil layers for the 3:2 slope, non-homogeneous 3D embankment example. Embankment height, *H* = 20 m. This represents a 3D extension of example 2 in Arai and Tagyo (1985).

Example 3 in Arai and Tagyo (1985) is identical to the homogeneous embankment (example 1) described above (table 6.12), but with the addition of a piezometric surface exiting at about the midpoint of the slope (fig. 6.6). Our 3D extension of this example is shown in figure 6.7. Pore-water pressure at any depth below the piezometric surface was computed using a hydrostatic assumption (section 2.4).

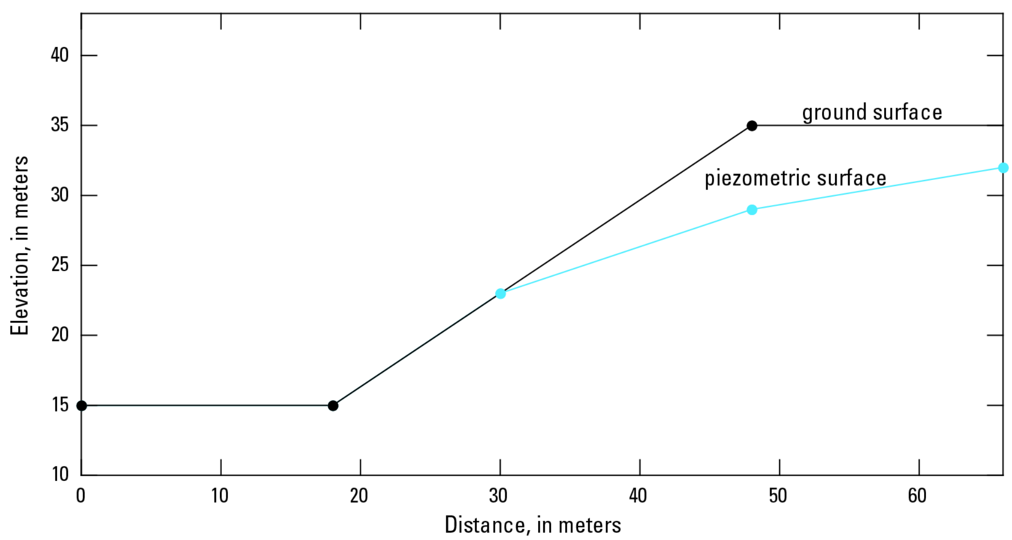


Figure 6.6. A 2D cross section of homogeneous 3:2 embankment example with a piezometric surface. Embankment height, *H* = 20 m. Example 3 in Arai and Tagyo (1985).

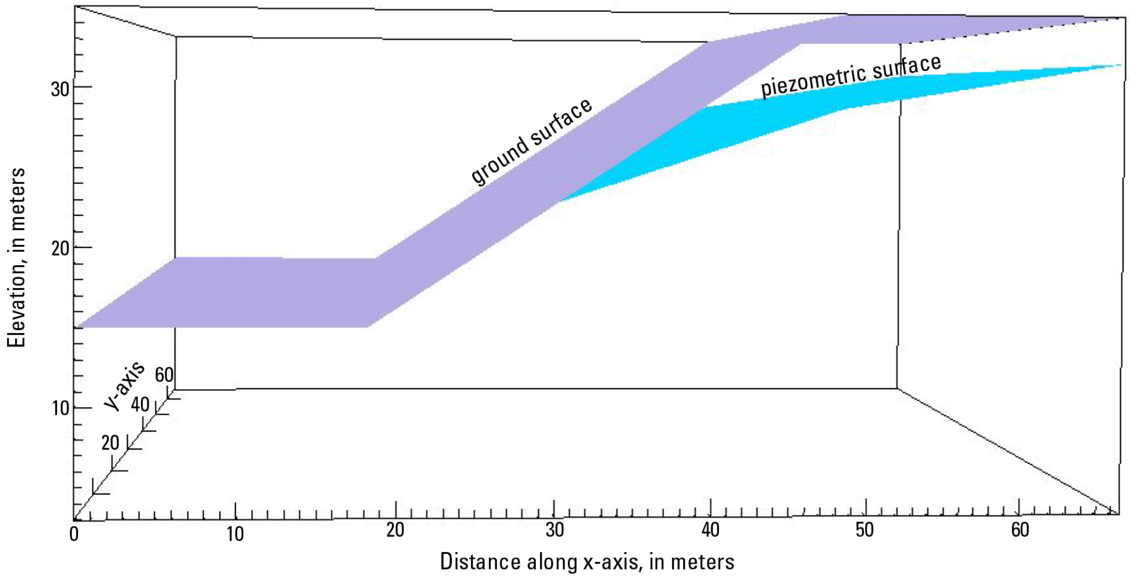


Figure 6.7. A 3D perspective view of 3:2 slope, homogeneous 3D embankment example with a piezometric surface. Embankment height, *H* = 20 m. This represents a 3D extension of example 3 in Arai and Tagyo (1985).

We used Bishop's simplified method to compare the 3D factors of safety computed by Scoops3D and CLARA-W for the three embankment examples of Arai and Tagyo (1985). Results are shown in table 6.14. Again, given the level of precision provided by CLARA-W, there is no difference between results from Scoops3D and CLARA-W for these three cases.

Table 6.14. Comparison of Scoops3D and CLARA-W results for the 3:2 slope 3D embankment examples.

[Factors of safety computed using 3D Bishop's simplified method. Embankments are 3D extensions of Arai and Tagyo's (1985) examples for a homogeneous embankment (example 1), non-homogeneous embankment (example 2), and homogeneous embankment with a piezometric surface (example 3)]

Arai and Tagyo's (1985) example number	Material properties	Piezometric surface	Scoops3D *F*	CLARA-W *F*	Percent difference from CLARA-W
1	Homogeneous	no	1.60	1.60	0.0
2	Non-homogeneous	no	0.54	0.54	0.0
3	Homogeneous	yes	1.27	1.27	0.0

6.4. Comparison with 2D Benchmark Solutions

Although Scoops3D was developed for the primary purpose of calculating 3D factors of safety throughout a 3D domain, it also computes a 2D factor of safety for a cross section through the approximate center of a 3D potential failure mass when the user selects the single trial surface option. Note that Scoops3D computes 2D solutions using a slightly different procedure than that typically used by 2D method of slices software (section 2.6). We compared the 2D factor of safety from Scoops3D with the 2D solution from CLARA-W, both using Bishop's simplified method, for a cross section through several of our 3D examples. We also compared 2D Ordinary and Bishop's simplified method solutions computed in Scoops3D with several 2D benchmark solutions (Arai and Tagyo, 1985; Donald and Giam, 1995; Rocscience Inc., 2010; Feng and Fredlund, 2012).

6.4.1. CLARA-W 2D Benchmark Solutions

Using a subset of the 3D benchmarking examples (section 6.2), we compared the 2D Bishop's factor of safety calculated by Scoops3D to the 2D solution from CLARA-W (O. Hungr Geotechnical Research Inc., 2010). For comparison with CLARA-W results, we used identical circular trial surfaces based on a slice through the estimated center of the 3D mass with a sphere center and radius identified previously through an extensive search for the 3D global minimum F.

For these scenarios, the factors of safety and areas computed using Scoops3D and CLARA-W are shown in table 6.15. Because CLARA-W only provides results with two decimal places, we use this precision for calculation of the differences. For most examples, the 2D factor of safety computed in Scoops3D is within 1.5 percent of the 2D factor of safety calculated by CLARA-W. Two examples, with $F << 1$ (wet with slope = 60°) have differences of ~7 and 15 percent. Such low values of F have little physical meaning and can lead to large percent differences when compared with other similar low values of F.

6.4.2. Published 2D Benchmark Solutions

A number of 2D benchmark solutions are commonly used for verification of 2D slope stability (Arai and Tagyo, 1985; Donald and Giam, 1995; Rocscience Inc., 2010; Feng and Fredlund, 2012). We compared the published 2D F for examples described in our 3D comparisons (sections 6.3.2 and 6.3.3) with 2D values of F computed using the 2D Ordinary and Bishop's simplified methods in Scoops3D. The benchmark 2D F values were derived from the following 2D software packages: SVSlope (Feng and Fredlund, 2012) and Slide (Rocscience Inc., 2010) that are reported in the SVSlope verification manual (Feng and Fredlund, 2012). We used CLARA-W (O. Hungr Geotechnical Research Inc., 2010) to supplement the comparisons. Computations of 2D Bishop's simplified F in Scoops3D showed a maximum difference of ~1.4 percent compared to other software packages (table 6.16) and computations of the Ordinary method F showed a maximum difference of ~0.4 percent (table 6.17).

Table 6.15. Comparison of 2D solutions from Scoops3D and CLARA-W for homogeneous embankments and cones, given different values of λ.

[Bishop's 2D factors of safety (*F*) and cross-sectional areas are computed for a slice through the center of the 3D critical surface identified by Scoops3D. Dry and wet scenarios with the same slope angle and λ are calculated using the same trial surface, and have the same cross-sectional area. Parameter r_u is pore-pressure ratio. °, degree; m, meter]

λ	r_u	Slope (°)	Scoops3D		CLARA-W		Comparison with CLARA-W	
			2D *F*	Area (m²)	2D *F*	Area (m²)	Percent difference 2D *F*	Percent difference area
Homogeneous embankments								
1.00	0	60	3.86	49.66	3.92	49.99	-1.5	-0.66
0.025	0	60	0.18	15.83	0.18	15.54	0.0	1.87
1.00	0.1	60	3.72	49.66	3.77	49.99	-1.3	-0.66
0.025	0.1	60	0.14	15.83	0.15	15.54	-6.7	1.87
1.00	0.4	60	3.28	49.66	3.33	49.99	-1.5	-0.66
0.025	0.4	60	0.034	15.83	0.04	15.54	-15.0	1.87
1.00	0	10	9.10	794.84	9.15	794.85	-0.5	0.00
0.025	0	10	1.13	178.17	1.13	178.09	0.0	0.04
1.00	0.1	10	8.63	794.84	8.68	794.85	-0.6	0.00
0.025	0.1	10	1.02	178.17	1.02	178.09	0.0	0.04
1.00	0.4	10	7.22	794.84	7.27	794.85	-0.7	0.00
0.025	0.4	10	0.70	178.17	0.70	178.09	0.0	0.04
Homogeneous cones								
1.00	0	30	8.51	1.13464×10^6	8.53	1.13399×10^6	-0.2	0.06
0.125	0	30	1.94	5.87655×10^5	1.95	5.87060×10^5	-0.5	0.10
0.025	0	30	0.82	3.22151×10^5	0.82	3.21631×10^5	0.0	0.16
1.00	0.1	30	8.21	1.13464×10^6	8.24	1.13399×10^6	-0.4	0.06
0.125	0.1	30	1.78	5.87655×10^5	1.79	5.87060×10^5	-0.6	0.10
0.025	0.1	30	0.73	3.22151×10^5	0.73	3.21631×10^5	0.0	0.16
1.00	0.4	30	7.32	1.13464×10^6	7.35	1.13399×10^6	-0.4	0.06
0.125	0.4	30	1.31	5.87655×10^5	1.31	5.87060×10^5	0.0	0.10
0.025	0.4	30	0.47	3.22151×10^5	0.47	3.21631×10^5	0.0	0.16

Table 6.16. Comparison of 2D results using Bishop's simplified method in Scoops3D and other software packages for published 2D benchmark examples.

[Other software includes Slide (Rocscience Inc., 2010), SVSlope (Feng and Fredlund, 2012), and CLARA-W (O. Hungr Geotechnical Research Inc., 2010). For comparison with CLARA-W, 2D Bishop's *F* computed inScoops3D was rounded to two digits after the decimal. Parameter ***eq*** is earthquake loading. °, degree]

Example	Material properties	*eq or water*	2D Bishop's *F*				Percent difference 2D Bishop's *F*		
			Software for comparison			Scoops3D			
			Slide	SVSlope	CLARA-W		Slide	SVSlope	CLARA-W
3:2 (~33.7 °) embankment from Arai and Tagyo (1985):									
Arai and Tagyo 1	Homogeneous	None	1.409	1.411	1.41	1.409	0.00	-0.14	0.0
Arai and Tagyo 2	Non-homogeneous	None	0.421	0.423	0.42	0.417	-0.95	-1.42	0.0
Arai and Tagyo 3	Homogeneous	Piezometric surface	1.117	1.120	1.11	1.113	-0.36	-0.63	0.0
2:1 (~26.6 °) embankment from Donald and Giam (1995):									
Donald and Giam 1a	Homogeneous	None	0.987	0.989	0.99	0.988	0.10	-0.10	0.0
Donald and Giam 1c	Non-homogeneous	None	1.405	1.405	1.40	1.397	-0.57	-0.57	0.0
Donald and Giam 1d	Non-homogeneous	***eq*** = 0.15	1.015	1.014	1.01	1.009	-0.59	-0.49	0.0

Table 6.17. Comparison of 2D results using the Ordinary method in Scoops3D and other software packages for published 2D benchmark examples.

[Other software includes Slide (Rocscience Inc., 2010) and SVSLOPE (Feng and Fredlund, 2012). Parameter ***eq*** is earthquake loading. °, degree]

Example	Material properties	*eq*	2D Ordinary *F*			Percent difference 2D Ordinary *F*	
			Software for comparison		Scoops3D		
			Slide	SVSlope		Slide	SVSlope
2:1 (~26.6 °) embankment from Donald and Giam (1995):							
Donald and Giam 1a	Homogeneous	None	0.947	0.945	0.944	-0.36	-0.15
Donald and Giam 1c	Non-homogeneous	None	1.232	1.231	1.227	-0.43	-0.35
Donald and Giam 1d	Non-homogeneous	***eq*** = 0.15	0.884	0.884	0.881	-0.34	-0.34

6.5. Testing of 3D Material Property and Pressure-Head Files

We tested the ability of Scoops3D to correctly utilize 3D distributions of material properties and pressure heads. Scoops3D can incorporate complex 3D distributions that cannot be replicated using only discrete layers. Because these complex 3D features are not commonly available in other software packages, there are no published 3D benchmark examples for comparison. To test these capabilities, we made use of two benchmark examples: (1) non-homogeneous material properties defined by layers (sections 6.3.2 and 6.3.3), and (2) groundwater conditions described by a piezometric surface (section 6.3.3). In both these cases, our original benchmark versions incorporated 3D data as layers (in ASCII raster files), in which the data are defined by either the elevation of the bottom of a layer or the elevation of a piezometric surface. Taken together, these layers represent a simplified form of 3D data and define properties throughout a 3D domain. To test the equivalence of these approaches, we created identical 3D distributions using 3D files, and then compared both approaches using examples that we already benchmarked with CLARA-W (section 6.3).

6.5.1. Comparison of Layer Files with 3D Material Properties File

Using our 3D extensions of the Arai and Tagyo (1985) example (2) (section 6.3.3) and the Donald and Giam (1995) example (1c) (section 6.3.2) with non-homogeneous properties defined by stratigraphic layers, we created 3D material property files equivalent to these layers by assigning properties to a 3D array. Extensive searches for the global minimum F using each of the two methods for specifying 3D material properties yielded the same results (table 6.18). Input files used for this comparison are provided in the Scoops3D *examples* folder (sections 7.2 and 7.3. Scoops3D examples C and I).

6.5.2. Comparison of Piezometric Surface with 3D Pressure-Head File

Using our 3D extension of the Arai and Tagyo (1985) example (3) (section 6.3.3) with a piezometric surface, we created an equivalent 3D pressure head file by assuming hydrostatic conditions beneath the piezometric surface. This 3D file contains pressure head at two locations (rather than a full 3D array) within each column underlying a DEM cell: (1) $h_p = 0$ at the water table, and (2) $h_p = h_t - h_z$, at a depth below the water table, where h_t = total head, h_p = pressure head, and h_z = elevation head. This configuration also tests the ability of Scoops3D to linearly interpolate pore pressure between known locations of pressure head. Our results from an extensive search for the global minimum F identify the same critical surfaces with the same factors of safety for both the Ordinary and Bishop's simplified methods (table 6.19).

Table 6.18. Comparison of computed 3D factor of safety in Scoops3D using the same material properties described in either layer files or a 3D material property file.

[Factor of safety (*F*) computed with both 3D Bishop’s simplified and Ordinary methods.°, degree]

Example	Scoops3D *F* with material properties described in layer files		Scoops3D *F* with material properties described in 3D material properties file		Percent difference *F*	
	*F*_Ordinary	*F*_Bishop	*F*_Ordinary	*F*_Bishop	Ordinary	Bishop
3:2 (~33.7 °) embankment from Arai and Tagyo (1985):						
Arai and Tagyo example 2	0.563	0.539	0.563	0.539	0.00	0.00
2:1 (~26.6 °) embankment from Donald and Giam (1995):						
Donald and Giam example 1c	1.372	1.514	1.372	1.514	0.00	0.00

Table 6.19. Comparison of computed 3D factor of safety in Scoops3D using the same groundwater configuration defined in either a piezometric surface file or a 3D pressure-head file.

[Factor of safety (*F*) computed with both 3D Bishop’s simplified and Ordinary methods]

Example	Scoops3D *F* with groundwater configuration described in piezometric surface file		Scoops3D *F* with groundwater configuration described in 3D pressure head file		Percent difference *F*	
	*F*_Ordinary	*F*_Bishop	*F*_Ordinary	*F*_Bishop	Ordinary	Bishop
Arai and Tagyo (1985) example 3	1.180	1.274	1.180	1.274	0.00	0.00

6.6. Number of Columns Tests

In addition to the verification tests discussed above, we assessed the sensitivity of Scoops3D calculations to the number of active columns in a potential failure mass. The accuracy of any solution determined by a discretization method is dependent on the level of discretization. Software packages for 2D limit-equilibrium analysis commonly have guidelines for the minimum number of slices to include in a trial surface. For 3D slope-stability analyses that use a method-of-columns limit-equilibrium analysis, the number of columns contained in a potential failure mass can affect the accuracy of results, such as total volume, potential failure surface area, and factor of safety, F. For example, Lam and Fredlund (1993) found that computation of F using their methods was inaccurate for potential failure masses with fewer than 400 columns. On the other hand, the user's guide for CLARA-W recommends using more than 1000 columns (O. Hungr Geotechnical Research Inc., 2010) to obtain accurate results and Huang and others (2002) found that more than 9,000 columns were required for a good solution using their methods. The approaches described by all of these investigators appear to involve calculations that use only columns with all four corners fully contained within the potential failure mass (that is, full columns).

Scoops3D utilizes partial (trial surface encompassing only 2 or 3 corners of a column) as well as full columns in stability computations, thus potentially reducing the number of active columns required for accurate results. However, Scoops3D analyses are typically designed to search for potential failures spanning a large range of volumes and (or) areas throughout a DEM, commonly entailing millions of potential failure masses containing a wide range of numbers of active columns.

To provide guidance about the desired numbers of active columns in a potential failure mass, we compared Scoops3D solutions for factor of safety, F, and volume computed with varying numbers of active columns in the potential failure mass for examples with differing topography, slope angles, and λ values (as defined in section 6.2), including cases of purely cohesive ($\lambda = \infty$) strength properties. Cases with more cohesive strength are sensitive to the accuracy of the computed trial slip surface area. Cases with more frictional strength are sensitive to the accuracy of the computed normal force on the base of the columns (a function of column weight and volume). For all tests, we compared the differences in computed F and volume, V, to a reference solution containing many active columns (designated as maxcol):

$$\%\ difference\ F = \left(\frac{F - F_{\max col}}{F_{\max col}} \right) 100 \text{, and} \tag{6.3}$$

$$\%\ difference\ V = \left(\frac{V - V_{\max col}}{V_{\max col}} \right) 100 \text{,} \tag{6.4}$$

where

F	is the factor of safety computed by Scoops3D for current number of active columns,
$F_{max\ col}$	is the factor of safety computed by Scoops3D with a large number of active columns,
V	is the volume computed by Scoops3D for current number of active columns, and
$V_{max\ col}$	is the volume computed by Scoops3D with a large number of active columns.

A common benchmark example used for number of columns testing is the analytical solution for a purely cohesive soil (Lam and Fredlund, 1993; Huang and others, 2002), as discussed in section 6.1. We compared factors of safety computed by Scoops3D for identical trial surfaces, but with decreasing numbers of active columns, to those obtained using an extremely high-resolution DEM (cell size = 0.00375 length units and maxcol = 150,292 columns) as the reference (fig. 6.8). For the potential failure mass using the high-resolution DEM, Scoops3D calculated F = 1.400, or ~0.1 percent less than the analytical solution of 1.402. Using the high-resolution DEM, the calculated volume was 0.655 cubic length units, which compares well with the volume of 0.654 cubic length units in an equivalent spherical cap. As the DEM decreased in resolution (fewer active columns in the potential failure mass), the value of F calculated by Scoops3D fluctuated relative to the analytical and high-resolution solutions from Scoops3D (fig. 6.8). For this example, our results indicate that at least 300 to 500 active columns are needed to obtain estimates of F, volume, and horizontal area within ~1 percent of the analytical solution.

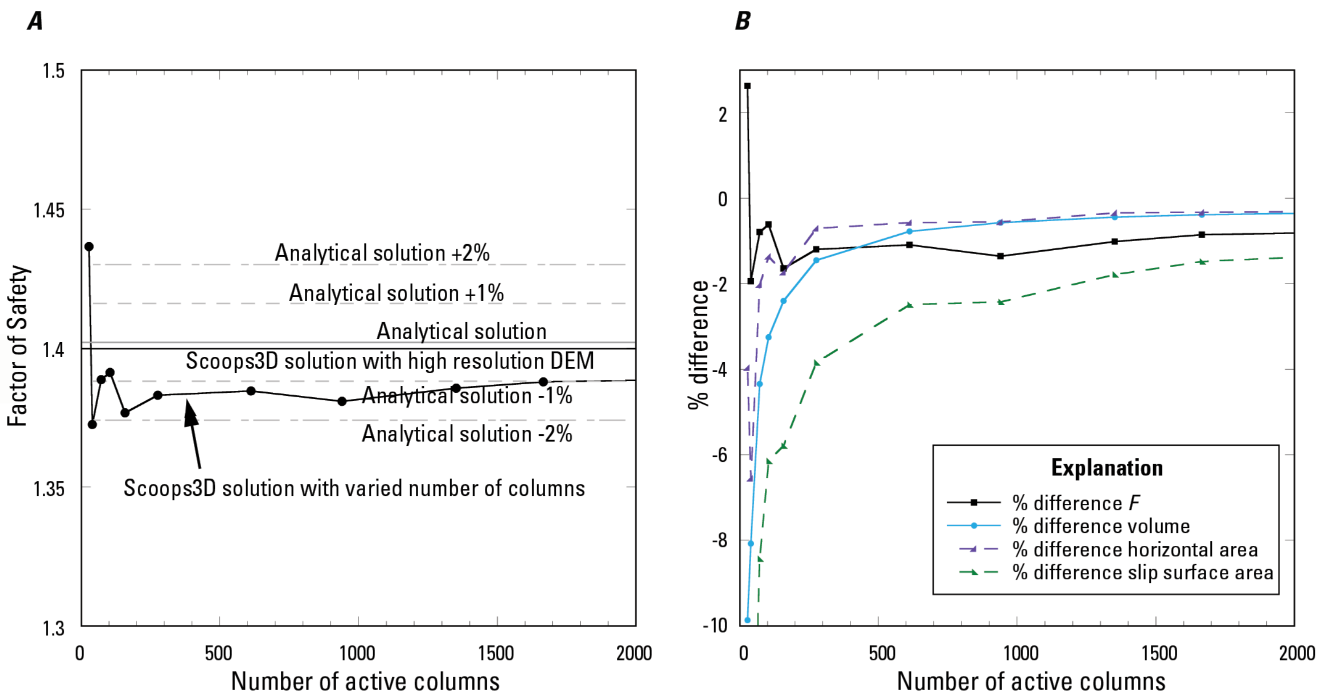


Figure 6.8. Graphs showing effects of number of active columns on computed 3D factor of safety, volume, horizontal area, and slip surface area for the purely cohesive example. Each case uses the same spherical potential failure mass as described in section 6.1. *A*, Computed 3D factor of safety, *F,* using Bishop's simplified method, versus number of active columns in the potential failure mass. The gray lines show the 3D analytical solution (solid gray) ±1 percent and ±2 percent (dotted gray) for comparison. The Scoops3D solution with a very high resolution DEM (solid black) for a potential failure mass containing 150,292 columns is 1.400 or 0.1 percent less than the analytical solution of 1.402. *B*, Percent difference in *F*, volume, horizontal area, and slip surface area versus number of active columns in the potential failure mass. Differences are relative to values obtained with the very high resolution DEM, as described above.

In addition to the analytical solution example for a purely cohesive soil, we analyzed the number of active column requirements for several of the embankment (height = 10 m) and cone (height = 1,000 m) examples described in section 6.2. For each example, the number of active columns in the reference solution was a function of the ground surface slope and potential failure size. The maximum number of active columns in the reference solutions ranged from 2,622 to 230,612. Percent differences from these reference solutions for factor of safety, *F*, and volume are shown in figure 6.9.

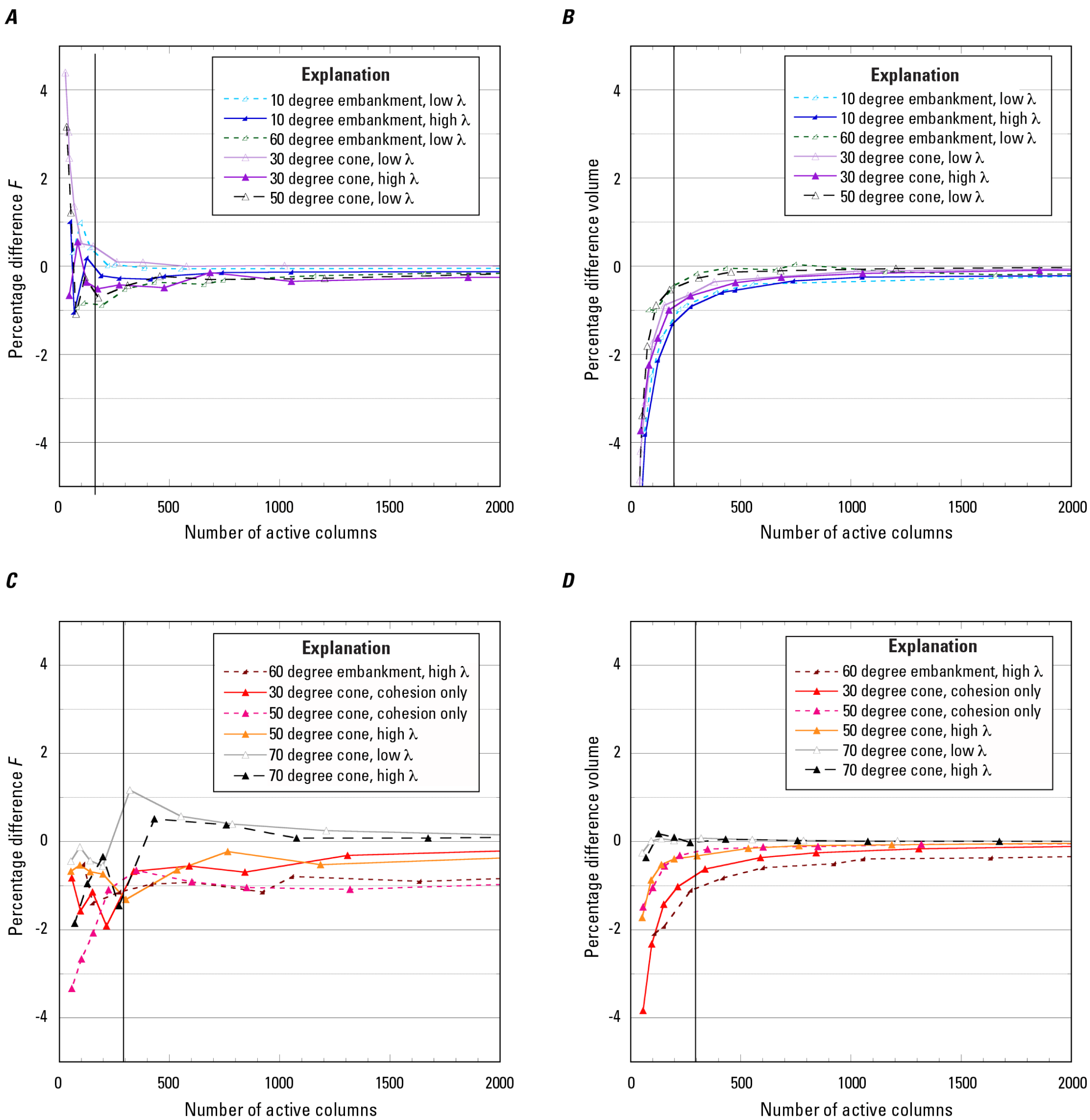


Figure 6.9. Graphs showing percent differences in Scoops3D results versus number of active columns in a potential failure mass for a variety of scenarios. Scenarios shown in *A* (factor of safety) and *B* (volume) are for low or moderately sloping topography (30° or less) or steeply sloping topography (50°–60°) with low λ, require at least ~200 active columns (vertical line) for results within 1 percent of the reference solutions. Scenarios shown in *C* (factor of safety) and *D* (volume) are for steeply sloping topography (50°–70°) or moderately sloping topography (30°) with cohesion only require at least 300 active columns (vertical line) for results within 1 percent of the reference solutions. Results use Bishop's simplified method of analysis. For the embankments, λ = 0.025 (low) and 1.0 (high). For the 30° cones, λ = 0.025 (low), 1.0 (high) and ∞ (cohesive strength only). For the 70° cones, λ = 0.0625 (low) and 1.0 (high). Material properties for low and high λ values are shown in tables 6.3 and 6.5. Results using greater than 2,000 active columns (including the reference solutions) are not shown.

We found that the number of active columns required for a reasonable solution for *F* varied with topography (embankments versus cones), ground surface slope, and λ (figs. 6.8 and 6.9). For low or moderately sloping topography (10º to 30º) or steeper topography with low λ values, Scoops3D analyses using as few as 200 active columns provided solutions within 1 percent of reference solutions that use significantly more active columns (fig. 6.9*A* and *B*). More active columns (300 to 500) were required for cases with very steep slopes (70º), steep slopes with high λ values, or cases with cohesive strength only. These column values are lower than those advocated by some other researchers (for example, Huang and others, 2002; O. Hungr Geotechnical Research Inc., 2010); we attribute this to Scoops3D's inclusion of partial columns, which provides a better estimation of volume and potential failure surface area than if these columns were excluded. Because Scoops3D counts partial columns as full columns when determining the number of active columns in a potential failure mass, the actual discretization in Scoops3D may be coarser than an equivalent example from the published studies using other models.

Increasing the number of active columns provides a better estimation of volume and *F*, but for many cases even a low number of active columns (<100) produced values of *F* within 2 percent of the reference solution. On the other hand, the accuracy of the volume calculation typically decreased rapidly when fewer than 200 active columns were used in the analysis. Therefore, we recommend using a DEM resolution that will encompass at least 200 active columns for potential failure masses with a size near the minimum specified by the user. Although some cases (for example, those with steep slopes or high λ values) may require a larger number of active columns (300 to 500 in some cases) to provide accurate results, preliminary assessments with fewer active columns may be useful.

To ensure that a sufficient number of active columns are contained in all potential failure masses to provide reasonably accurate results, it is crucial to select an adequate DEM resolution. A DEM resolution that provides more than 500 active columns (or more than 200 in many cases) in the smallest potential failure masses will provide reasonable estimates of *F* and potential failure size. If runtime and (or) computer memory requirements are of concern (section 5.2), however, it may be desirable to minimize the DEM resolution and therefore reduce the number of active columns in a given potential failure mass (section 5.3.4). To help assess DEM resolution adequacy, Scoops3D allows the user to select a desired minimum number of active columns (***limcol***) to be included in a potential failure mass. Any potential failure mass with fewer active columns will still be included in the analysis but will be flagged so the user can assess their importance to the overall results (section 4.5.2.2). The user can then adjust the discretization level of the problem domain or the range of potential failure sizes to be considered based on this knowledge.

6.7. Symmetry Tests

Scoops3D has the ability to compute factors of safety of potential failure masses regardless of the orientation of their potential slip direction relative to the x- and y-axes of the DEM. This ability differs from that of most other slope stability software packages, which commonly require the user to align the topography (or presumed slip direction) to the coordinate axes. For example, the 3D CLARA-W software (O. Hungr Geotechnical Research Inc., 2010) requires the slope to increase in elevation from left to right (the y-axis in CLARA-W), in alignment with the grid. Because Scoops3D can analyze potential failure masses with slip directions at any orientation relative to the DEM coordinate axes, it can fully search a DEM.

To assure that Scoops3D can accurately compute the factor of safety, *F*, regardless of slip direction, we created factor-of-safety maps for a symmetric cone. These examples compute *F* for more than 80,000 potential failure masses. Ideally, *F* computed at identical elevations would be the same regardless of orientation relative to the axes of the coordinate system. Our symmetry tests show that only small discrepancies in *F* (< 0.1 to 0.2 percent) occur at different locations around the cone. The pattern of variability depends on λ values (fig. 6.10).

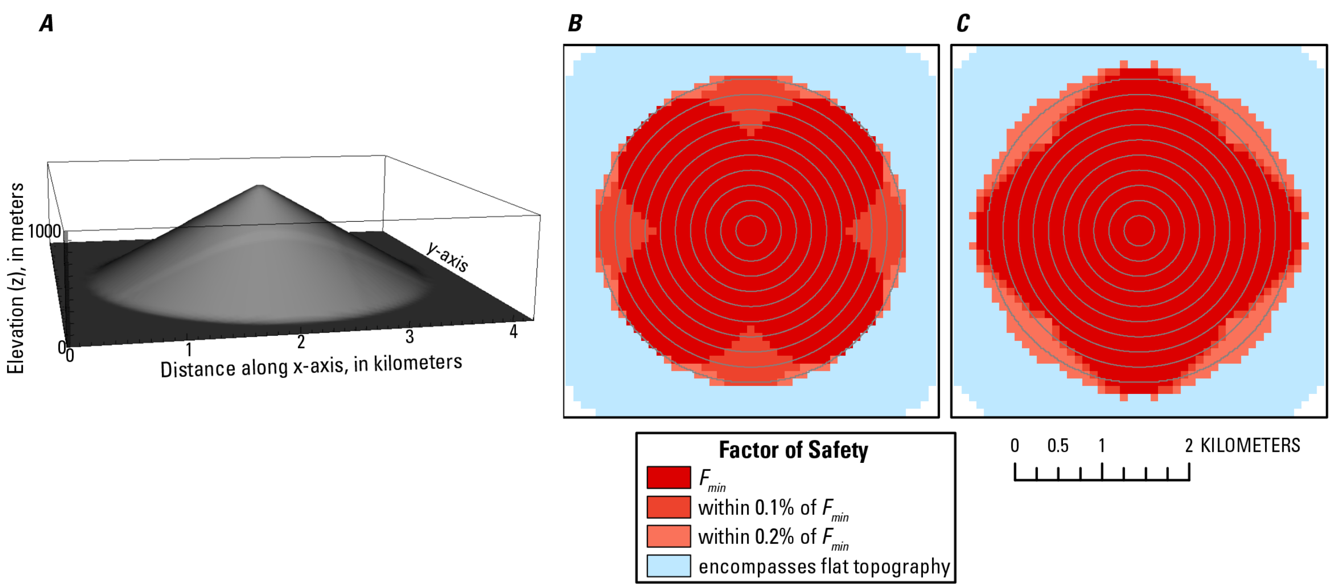


Figure 6.10. Perspective and map views of cones showing the results of the symmetry tests. Factor of safety shown for each DEM cell is computed relative to the global minimum factor of safety F_{min} using Bishop's simplified method. *A*, Perspective view of 30° cone DEM with height, *H* = 1000 m. *B*, Plan view showing *F* results for a cone with low λ = 0.025. *C*, Plan view showing *F* results for a cone with high λ = 1.0. Material properties for low and high λ values are shown in table 6.5. Perspective view created using VisIt software and maps created using Esri ArcMap software.

6.8. Tests of Partially Saturated Suction Effects

As discussed in section 2.2, Scoops3D can include the effects of suction stress from partially saturated earth materials in its computation of slope stability. In partially saturated (or unsaturated) materials, pore-water pressures are negative relative to atmospheric pressure, and they impart a suction stress. We are not aware of analytical solutions for 3D slope stability with suction stresses that would enable a direct comparison with Scoops3D results. To test the reasonableness of Scoops3D inclusion of suction stress, we examine the variation in factor of safety, *F*, with differing water contents (or suction stresses), computed using two hypothetical soils with different properties. Given these soils, as uniform water content changes, computed *F* should directly reflect variations in suction stress; that is, peaks in suction stress should lead to more stable slopes with higher values of *F*. We evaluate suction effects using van Genuchten (1980) and Fredlund and Xing (1994) soil-water characteristic curves (SWCC) for the two soils. We also compare our Fredlund and Xing SWCC results with those calculated using the SVSlope software (Fredlund and others, 2009).

Our suction stress analyses use three straight 10-m high embankments with slopes of 10º, 30º and 50º. Properties for the two soils, including both van Genuchten and Fredlund and Xing SWCC shape parameters are shown in table 6.20. One set of hypothetical values is typical of sand and the other is typical of clay. The soil-water characteristic curves and suction-stress curves for the two materials, for both approaches are shown in figure 6.11. Note that the sand suction-stress curve has a pronounced peak at a matric suction of about 8 kPa (for this material).

Table 6.20. List of parameters for two materials (sand and clay) used in the partially saturated suction tests.

[Parameters for materials: c is cohesion, ϕ is angle of internal friction, γ_s is saturated unit weight, θ_r is residual volumetric water content, and θ_s is saturated volumetric water content. º, degree; kN, kilonewton; kPa, kilopascal; m, meter]

Parameter	Sand	Clay
c (kPa)	1	15
ϕ (°)	34	28
γ_s (kN/m^3)	20	18
θ_s	0.35	0.5
van Genuchten parameters		
van Genuchten θ_r	0.05	0.1
van Genuchten α (kPa^{-1})	0.1	0.01
van Genuchten n	5	2
Fredlund and Xing parameters		
Fredlund and Xing θ_r	0.092	0.22
Fredlund and Xing a (kPa)	8.69	68.97
Fredlund and Xing n	6.82	3.61
Fredlund and Xing m	0.844	0.417
Fredlund and Xing ψ_r (kPa)	16.8	316

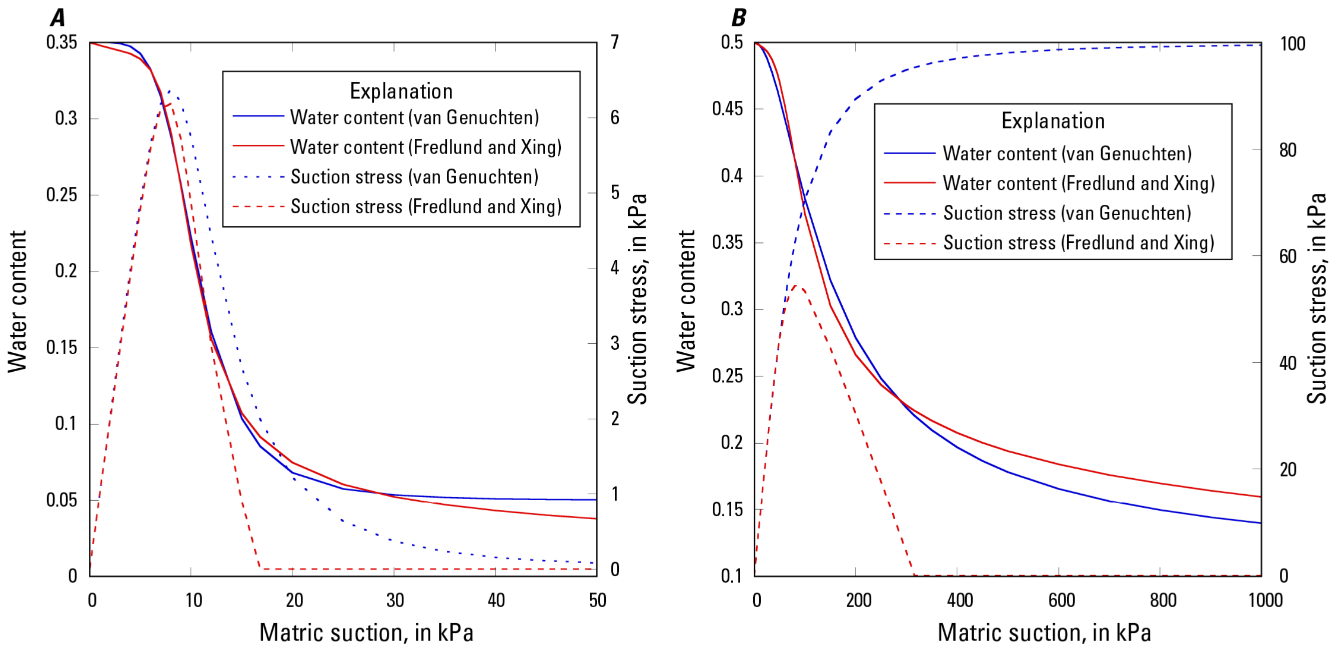


Figure 6.11. Graphs showing soil-water characteristic curves (water content versus matric suction) and suction-stress curves for two materials, sand and clay, used in the suction tests. The graphs show water content and suction stress using two different equations (van Genuchten, 1980; Fredlund and Xing, 1994). Material parameters are listed in table 6.20. Note different x- and y-axis scales. Suction stress is the product of matric suction and the effective degree of saturation, S_e (see equation 2.8). *A,* Sand. *B,* Clay.

Using Scoops3D, we examined the effect of variations in suction stress by constructing a series of scenarios, each having uniform values of effective degree of saturation, S_e, matric suction, and suction stress. The scenarios cover the various combinations of the two soils and three embankment slopes. We compared the relative effects on slope stability in two ways. For both the van Genuchten and Fredlund and Xing curves, we used a fixed trial surface for each scenario that was identified by Scoops3D as the least-stable (critical) surface for the corresponding dry embankment. This same fixed trial surface was then analyzed for each suction-stress scenario. For the van Genuchten curves, we also allowed Scoops3D to search for the critical surface (minimum F) for each value of matric suction.

Results from these two approaches are shown in figure 6.12. As might be anticipated, factors of safety on the critical surfaces are slightly lower than those on the fixed trial surfaces. For both sand and clay materials, computed factors of safety with varying matric suctions follow the same patterns as their respective suction-stress curves (fig. 6.11). In sand, a peak in stability (higher factor of safety) occurs with a matric suction of about 8 kPa for both SWCC methods. In the clay with a van Genuchten SWCC, stability continues to increase with increasing matric suction, as the scenarios shown are wetter than residual water content, θ_r. For the clay with a Fredlund and Xing SWCC, the suction-stress curve has a different shape and stability effects are reduced in drier scenarios. For both sand and clay with Fredlund and Xing curves, factors of safety for scenarios with suctions greater than residual, ψ_r, matric suction is equal to zero, therefore, factors of safety are equal to the value with no matric suctions. For all cases, the same patterns occur in embankments with different slopes, with overall lower factors of safety for steeper embankments.

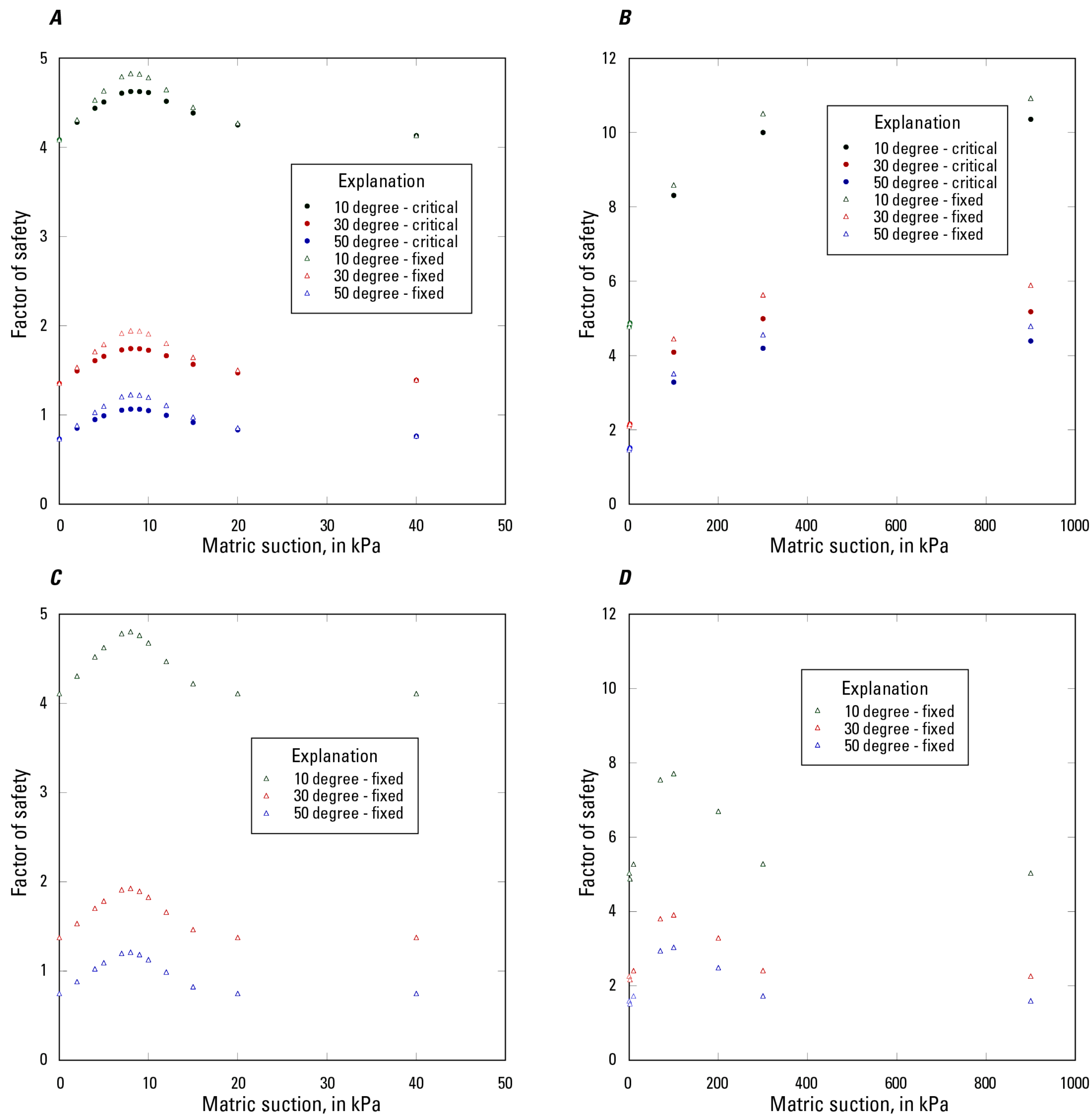


Figure 6.12. Graphs showing computed 3D factor of safety and matric suction for partially saturated sand and clay in three different embankments with different soil-water characteristic curve (SWCC) approaches. Embankments have slopes of 10º, 30º, and 50º. Fixed values for each case use a trial surface based on the least-stable dry trial surface whereas critical values result from a search for the minimum *F* given the different matric-suction conditions. *A*, Sand, using van Genuchten SWCC. *B*, Clay using van Genuchten SWCC. C, Sand using Fredlund and Xing SWCC. D, Clay using Fredlund and Xing SWCC.

Table 6.21. Comparison of 3D factor-of-safety (*F*) results using Bishop's simplified method in Scoops3D and SVSlope for partially saturated embankments.

[Results are for a fixed trial surface based on the least-stable trial surfaces in dry embankments with slopes of 10º, 30º, and 50º. kN, kilonewton; kPa, kilopascal; m, meter]

Matric suction (kPa)	Unit weight (kN/m^3)	Scoops3D Bishop's *F*			SVSlope Bishop's *F*			Percent difference *F*		
		10 degree embankment	30 degree embankment	50 degree embankment	10 degree embankment	30 degree embankment	50 degree embankment	10 degree embankment	30 degree embankment	50 degree embankment
Sand										
No matric suction	17.47	4.109	1.374	0.748	4.109	1.376	0.751	-0.01	-0.15	-0.40
2	19.97	4.310	1.534	0.882	4.310	1.539	0.890	0.00	-0.34	-0.90
4	19.93	4.530	1.709	1.029	4.531	1.718	1.041	-0.02	-0.55	-1.20
5	19.90	4.635	1.792	1.098	4.636	1.803	1.114	-0.02	-0.61	-1.40
7	19.68	4.797	1.920	1.206	4.797	1.935	1.225	-0.01	-0.76	-1.56
8	19.43	4.817	1.936	1.219	4.818	1.951	1.239	-0.03	-0.76	-1.60
9	19.08	4.777	1.904	1.193	4.778	1.919	1.212	-0.03	-0.76	-1.60
10	18.70	4.689	1.835	1.134	4.691	1.848	1.152	-0.04	-0.71	-1.54
12	18.09	4.476	1.666	0.993	4.477	1.675	1.005	-0.02	-0.56	-1.24
15	17.62	4.223	1.465	0.824	4.224	1.470	0.831	-0.01	-0.34	-0.81
20	17.47	4.109	1.374	0.748	4.109	1.376	0.751	-0.01	-0.15	-0.40
Clay										
No matric suction	15.30	5.033	2.260	1.599	5.038	2.262	1.599	-0.11	-0.11	0.01
2	18.00	4.883	2.168	1.520	4.888	2.169	1.520	-0.10	-0.06	0.03
10	17.98	5.283	2.413	1.732	5.289	2.416	1.732	-0.12	-0.12	-0.03
70	17.35	7.597	3.838	2.974	7.611	3.843	2.974	-0.18	-0.13	-0.02
100	16.74	7.765	3.942	3.065	7.780	3.947	3.065	-0.19	-0.14	-0.01
200	15.71	6.734	3.306	2.508	6.744	3.309	2.505	-0.15	-0.08	0.10
300	15.34	5.286	2.415	1.733	5.288	2.415	1.728	-0.04	0.01	0.31
900	15.30	5.033	2.260	1.599	5.038	2.262	1.599	-0.11	-0.11	0.01

Using the Fredlund and Xing SWCC approach, we also compared factor-of-safety results from Scoops3D with SVSlope, both using Bishop's simplified method of analysis. The results, for three different embankments and two soils, are shown in table 6.21. Most of the differences are within 1 percent; some scenarios with steeper embankments differ by ~1.6 percent. All of our test results suggest that Scoops3D is able to properly incorporate the effects of suction stress into its stability computations.

6.9. Discussion

Our testing and verification of Scoops3D demonstrates general agreement between Scoops3D results, 3D analytical solutions, and 3D benchmark solutions for both computed factors of safety and potential failure volumes. The 3D benchmark solutions using CLARA-W show the best agreement with the Scoops3D results (typically less than 0.1 percent difference in factor of safety and volume). This agreement is expected, as CLARA-W uses the same factor of safety formulation for Bishop's simplified method and allows direct comparisons for identical spherical trial surfaces. Likewise, comparisons of 2D factors of safety for single trial surfaces agreed well (typically within 1 percent) with CLARA-W, as well as with solutions to benchmark examples published in 2D software verification manuals (Rocscience Inc., 2010; Feng and Fredlund, 2012).

Our testing also showed:

- Compared to 3D analytical chart solutions, factors of safety computed by Scoops3D using Bishop's simplified method are within 1 to 9 percent for embankments and 0 to 2 percent for cones. These differences are likely due to differences in the assumed trial surface shape (log-spiral in the chart solutions vs. spherical in Scoops3D).
- Results of examples comparing material layers with an equivalent 3D material property file agreed for our benchmark examples (section 6.5.1).
- Results of examples comparing a piezometric surface file with an equivalent 3D pressure head file agreed for our benchmark examples (section 6.5.2).
- Scoops3D typically provides good estimates of potential failure volume and factor of safety using as few as ~200 active columns in a potential failure mass (section 6.6). Cases with high λ values (more cohesive strength) or steep slopes may require more (~300 to 500) active columns.
- For potential failure masses with slip directions that are not aligned to the coordinate axes, Scoops3D computes factors of safety to within 0.1 to 0.2 percent regardless of slip orientation (section 6.7).

Chapter 7. Examples

In this chapter, we provide multiple examples that illustrate many of the capabilities of Scoops3D. Files in the examples can:

- Aid the user in learning to run Scoops3D and examine output files. Once Scoops3D is installed, our examples should execute without any user modifications to the files.
- Serve as templates to help the user construct new files for scenarios similar to a particular example. The examples include a wide variety of situations with proper formats for the main parameter input files, ASCII raster grid files, and 3D input files for Scoops3D.
- Allow the user to compare previous results with those generated using their current computer system. This is especially valuable if the user recompiles Scoops3D to execute on their system.

All input and output files for each example are contained in the Scoops3D *examples* folder. Examples include some of the generic topographies (embankments and cones) used for testing and verification of Scoops3D (chapter 6), including our 3D extension of published 2D verification examples (Arai and Tagyo, 1985; Donald and Giam, 1995). We also include several real-world topographies based on DEMs from two regions in Washington State, USA – the Mount St. Helens volcano edifice and a section of coastal bluffs in Seattle. These are derived from previously published work (Reid and others, 2000; Brien and Reid, 2007; Brien and Reid, 2008).

The examples illustrate a variety of scenarios describing the 3D domain underlying the DEM (table 7.1). They include three variations of material properties: (1) homogeneous, (2) non-homogeneous defined in layer files, and (3) non-homogeneous defined in a 3D material property file. Examples include three variations of groundwater configurations: (1) a pore-pressure ratio, r_u, (2) a piezometric surface file, and (3) a 3D pressure-head file. Also included are examples of three different search methods: (1) box, (2) single surface, and (3) file search. Some of our box searches of generic topographies (embankments and cones) represent special situations wherein we seek to identify only the global minimum factor of safety (rather than assess stability everywhere) in a symmetric topography for testing purposes. For these situations, it is adequate to search a single 2D vertical cross section through the lattice above the center of the DEM. This type of search can identify the global minimum factor of safety in symmetric topography; however, it does not utilize the ability of Scoops3D to identify the least-stable surface for every DEM cell. A more complete search (not just a vertical cross section) is recommended for DEMs that represent real-world topography.

Table 7.1. Summary of Scoops3D examples, including main parameter input files, DEMs and configuration parameters.

[Full DEM search = 'No' indicates a Box search of a 2D vertical cross section above the center of the DEM. This type of search does not utilize the ability of Scoops3D to identify the least-stable surface for every DEM cell and is not recommended for DEMs that represent real-world topography. *H* is embankment height and ***eq*** is earthquake loading. m, meter]

Section	Description, reference, and DEM file name	Name of subfolder	Example	Main parameter input file (.scp)	Material properties and method of specification	Groundwater configuration and method of specification	*eq*	Search method	Full DEM search
7.2	Arai and Tagyo embankment configurations	*AraiTagyo*	A	*A_emb20*	Homogeneous	None	0	Box	No
	embankment, *H* =20 m, 3:2 slope		B	*B_emb20nonhomog*	Non-homogeneous, layers	None	0	Box	No
	(Arai and Tagyo, 1985)		C	*C_emb20nonhomog3D*	Non-homogeneous, 3D file	None	0	Box	No
	emb20DEM.asc		D	*D_emb20wet*	Homogeneous	Piezometric surface file	0	Box	No
			E	*E_emb20wet3D*	Homogeneous	3D pressure-head file, derived from piezometric surface	0	Box	No
7.3	Donald and Giam embankment configurations	*DonaldGiam*	F	*F_emb10*	Homogeneous	None	0	Box	No
	embankment, *H* = 10 m, 2:1 slope		G	*G_emb10single*	Homogeneous	None	0	Single	No
	(Donald and Giam, 1995)		H	*H_emb10nonhomog*	Non-homogeneous, layers	None	0	Box	No
	emb10DEM.asc		I	*I_emb10nonhomog3D*	Non-homogeneous, 3D file	None	0	Box	No
			J	*J_emb10nonhomogeq*	Non-homogeneous, layers	None	0.15	Box	No
7.4	Symmetric cone configurations	*cone*	K	*K_conehi*	Homogeneous	None	0	Box	No
	cone, *H* = 1000 m, 30 degree slope		L	*L_conemed*	Homogeneous	None	0	Box	No
	Scoops3D manual (section 6.2.2)		M	*M_conelo*	Homogeneous	None	0	Box	No
	cone1000DEM.asc		N	*N_conemedfullsearch*	Homogeneous	None	0	Box	Yes
			O	*O_conemedru*	Homogeneous	Pore-pressure ratio (r_u)	0	Box	No

Section	Description, reference, and DEM file name	Name of subfolder	Example	Main parameter input file (.scp)	Material properties and method of specification	Groundwater configuration and method of specification	*eq*	Search method	Full DEM search
7.5	southwestern Seattle, Washington (Brien and Reid, 2007) *seaclipDEM.asc*	*Seattle*	P	*P_seadry*	Non-homogeneous, layers	None	0	File	Yes
			Q	*Q_seawet*	Non-homogeneous, layers	3D pressure-head file, derived from groundwater flow model	0	File	Yes
7.6	Mount St. Helens, Washington (Reid and others, 2000) *sthel_res100mDEM.asc*	*StHelens*	R	*R_sthel*	Homogeneous	None	0	Box	Yes

.

The sections below provide a description of each example, followed by an explanation of the input files. For each example, the main parameter input file (.scp file) is located in a subfolder within the Scoops3D *examples* folder (as listed in table 7.1). Within each of these subfolders, an *input* subfolder contains all additional Scoops3D input files. Also, for each example, a folder containing all original input and output files is located in the folder labeled *examples/original_files*.

All Scoops3D input files can be viewed in a text editor; however, we recommend opening the main parameter input files (.scp files) in the graphical user interface (GUI) program Scoops3D-i (**File > Open**). Other input files (such as ASCII raster files and 3D files) can also be viewed from Scoops3D-i by selecting **View > ASCII Text File** or by using a text editor of the user's choice. We suggest that users examine several of the examples using the methods described in section 7.1 to gain insight into the capabilities of Scoops3D and to aid in construction of their own analyses. Examples demonstrating specific Scoops3D options can be found by examining table 7.1.

7.1. Running an Example

To illustrate how to use the examples, we show screenshots from Scoops3D-i that demonstrate opening, viewing, and running Scoops3D example C (*C_emb20nonhomog3D.scp*) in the *AraiTagyo* folder. This dry, non-homogeneous, 20-m high, 3:2 embankment example is a 3D extension of a commonly used 2D verification example, described in the testing section (sections 6.3.3 and 6.5.1; Arai and Tagyo (1985), example 2), and demonstrates the use of a 3D material properties file (section 4.4.2). Before running this example, the user should be familiar with the operation of Scoops3D-i (section 4.3).

When viewing the files, be careful not to select **File > Save** as this action will overwrite the original example file. If the user would like to save modifications, use **File > Save As** and assign a new file name and (or) location for the modified file to avoid overwriting the original example.

7.1.1. Opening and Viewing a .scp File

After launching Scoops3D-i, select **File > Open** from the main window menu bar, navigate to the appropriate folder (directory) containing the Scoops3D *examples* folder and locate the subfolder *AraiTagyo*. Within this subfolder select the file *C_emb20nonhomog3D.scp* and click **Open**. The main Scoops3D-i window displays information contained in the .scp input file (fig. 7.1). The top two sections of the window display a description of the file, DEM file name, and information about the DEM. The **Subsurface Conditions** section of the window shows that this example uses a 3D material properties file with no groundwater and no earthquake loading. The **Stability Analysis** section of the window shows that this example uses Bishop's simplified method, and the extent of the search lattice is defined by a box.

The example can be run directly from this window; however, we step through the various components of the example to illustrate features and file formats that could aid the user in constructing their own files.

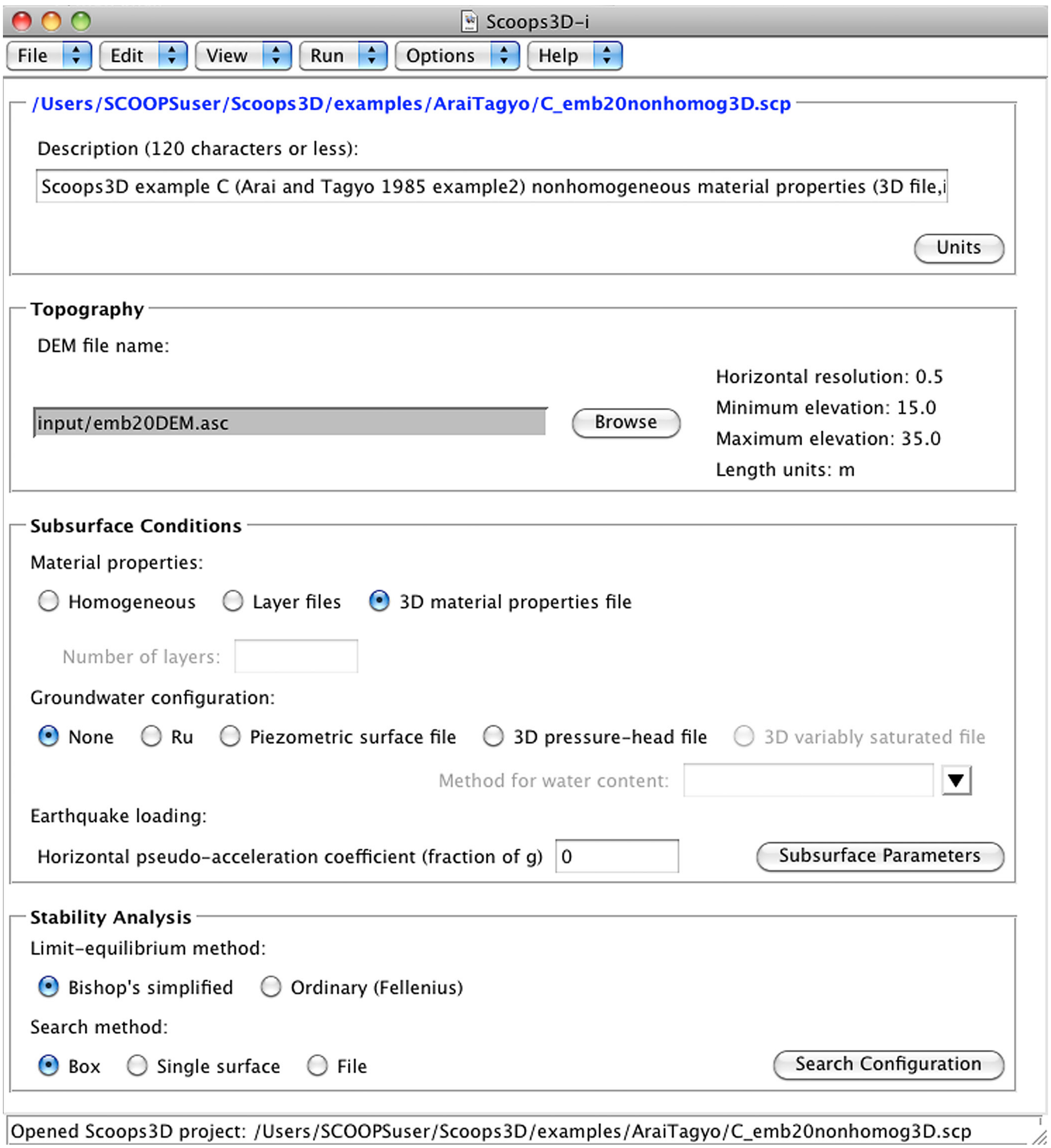


Figure 7.1. Screenshot of the main Scoops3D-i window after opening example C. This example (file name: *C_emb20nonhomog3D.scp*) uses a 3D material properties file, no groundwater configuration, no earthquake loading, Bishop's simplified limit-equilibrium method, and the box search method.

The details of the subsurface parameters specified for this example can be examined by clicking the **Subsurface Parameters** button. The **Subsurface Parameters** child window shows the parameters for the 3D material properties file, including a valid file name associated with the example, the method of interpreting the vertical distribution of properties, and selection of the parameters contained in the 3D material properties file (fig. 7.2). In this example, all of the material properties (cohesion, angle of internal friction, and total unit weight) are contained in the 3D material properties file (and are therefore set to the default value of -1 in the .scp file, see section 4.4.1.1.4.2). Deselecting any of the check boxes would require the user to provide a valid value for the specified parameter in the boxes below the **Remaining uniform properties** as well as creation of a new 3D material properties file containing only the parameters needed in the 3D material properties file. Click **Cancel** to return to the main window without making changes.

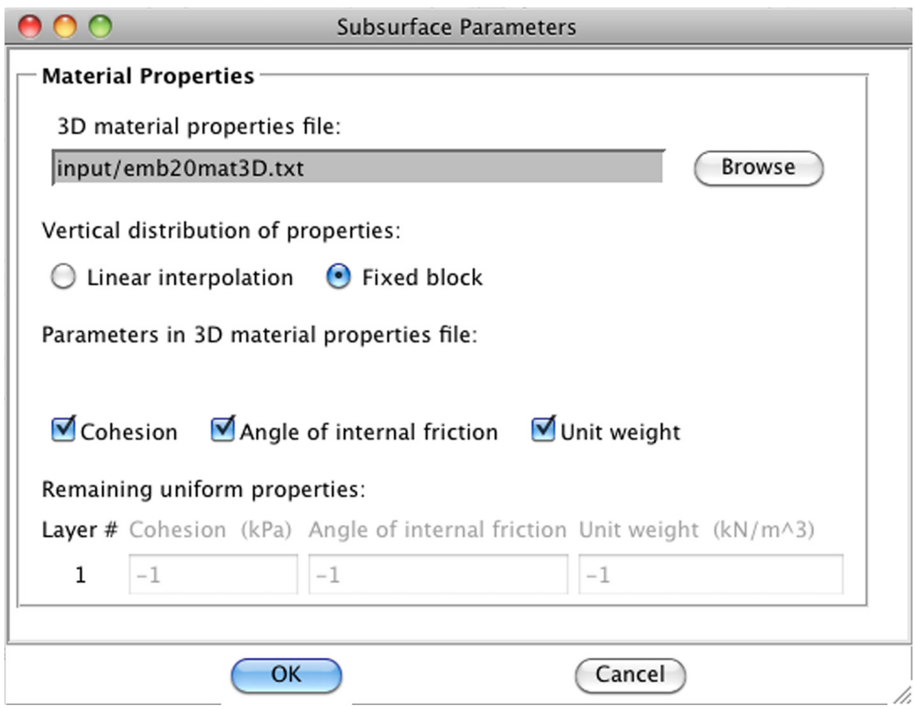
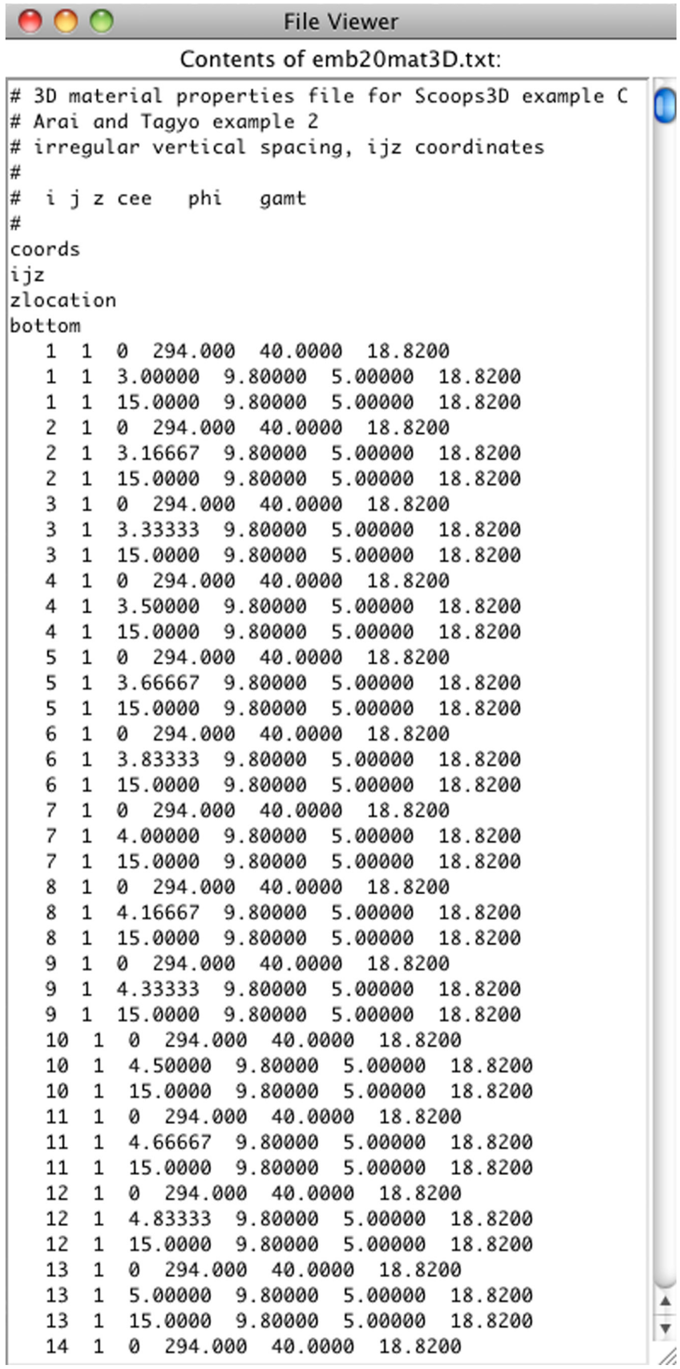


Figure 7.2. Screenshot of **Subsurface Parameters** child window for example C. File name for example: *C_emb20nonhomog3D.scp*. Parameters for the 3D material properties file, including the 3D material properties file name, the method of interpreting the vertical distribution of properties, and identification of the parameters contained in the 3D material properties file are shown.

After returning to the main Scoops3D-i window (fig. 7.1), select **View** > **ASCII Text File** from the main window menu bar. Navigate to the *input* subfolder within the *AraiTagyo* subfolder and select the 3D material properties file *emb20mat3D.txt*. Clicking **Open** will show a **File Viewer** window displaying the contents of the 3D material properties file (fig. 7.3). This file demonstrates the file format and required header information for a

3D input file using ‘ijz’ coordinates (section 4.4.2.2.1). Click the close button at the top of the **File Viewer** window and return to the main Scoops3D-i window (fig. 7.1).



File Viewer

Contents of emb20mat3D.txt:

```
# 3D material properties file for Scoops3D example C
# Arai and Tagyo example 2
# irregular vertical spacing, ijz coordinates
#
#   i j z cee   phi   gamt
#
coords
ijz
zlocation
bottom
   1  1  0  294.000  40.0000  18.8200
   1  1  3.00000  9.80000  5.00000  18.8200
   1  1  15.0000  9.80000  5.00000  18.8200
   2  1  0  294.000  40.0000  18.8200
   2  1  3.16667  9.80000  5.00000  18.8200
   2  1  15.0000  9.80000  5.00000  18.8200
   3  1  0  294.000  40.0000  18.8200
   3  1  3.33333  9.80000  5.00000  18.8200
   3  1  15.0000  9.80000  5.00000  18.8200
   4  1  0  294.000  40.0000  18.8200
   4  1  3.50000  9.80000  5.00000  18.8200
   4  1  15.0000  9.80000  5.00000  18.8200
   5  1  0  294.000  40.0000  18.8200
   5  1  3.66667  9.80000  5.00000  18.8200
   5  1  15.0000  9.80000  5.00000  18.8200
   6  1  0  294.000  40.0000  18.8200
   6  1  3.83333  9.80000  5.00000  18.8200
   6  1  15.0000  9.80000  5.00000  18.8200
   7  1  0  294.000  40.0000  18.8200
   7  1  4.00000  9.80000  5.00000  18.8200
   7  1  15.0000  9.80000  5.00000  18.8200
   8  1  0  294.000  40.0000  18.8200
   8  1  4.16667  9.80000  5.00000  18.8200
   8  1  15.0000  9.80000  5.00000  18.8200
   9  1  0  294.000  40.0000  18.8200
   9  1  4.33333  9.80000  5.00000  18.8200
   9  1  15.0000  9.80000  5.00000  18.8200
   10  1  0  294.000  40.0000  18.8200
   10  1  4.50000  9.80000  5.00000  18.8200
   10  1  15.0000  9.80000  5.00000  18.8200
   11  1  0  294.000  40.0000  18.8200
   11  1  4.66667  9.80000  5.00000  18.8200
   11  1  15.0000  9.80000  5.00000  18.8200
   12  1  0  294.000  40.0000  18.8200
   12  1  4.83333  9.80000  5.00000  18.8200
   12  1  15.0000  9.80000  5.00000  18.8200
   13  1  0  294.000  40.0000  18.8200
   13  1  5.00000  9.80000  5.00000  18.8200
   13  1  15.0000  9.80000  5.00000  18.8200
   14  1  0  294.000  40.0000  18.8200
```

Figure 7.3. Screenshot of **File Viewer** window showing the contents of the 3D material properties file used in example C. File name for example: *emb20mat3D.txt*.

Next, click the **Search Configuration** button to examine the details of the search configuration. The radio buttons in the **Search Configuration** child window show that volume is the selected size criteria (fig. 7.4). Scoops3D will search for potential failures between the minimum (within a tolerance) and maximum volume specified. Other parts of the window show the number of slip directions, and the extent and resolution of the search lattice (the user may need to expand the window on their screen to see all fields). Note that the resolution of the horizontal extent is specified as a multiplier of the DEM resolution and this example searches only a 2D cross section through the center of the DEM (so minimum j = maximum j = 67). This is a special search used to locate the global minimum factor of safety for a uniform embankment. See section 6.3.3 for a description of the problem setup. For a thorough search of a DEM, the horizontal extent typically should match or exceed the limits of the DEM. Click **Cancel** to return to the main window without making changes.

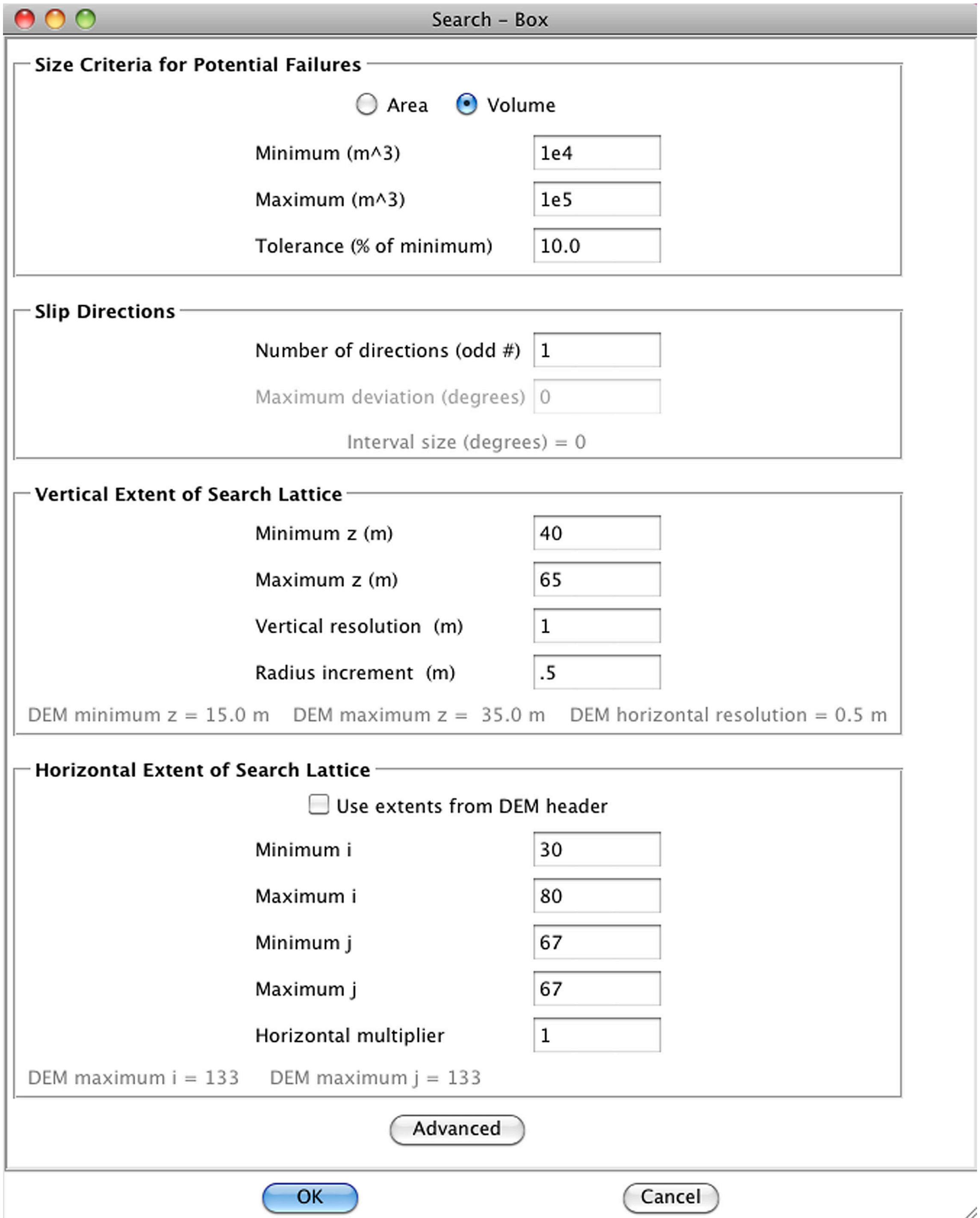


Figure 7.4. Screenshot of **Search Configuration** child window for example C. File name for example: *C_emb20nonhomog3D.scp*. Parameters for the box search include minimum and maximum sizes for the selected size criteria, number of slip directions, and vertical and horizontal spacing and extents of the 3D search lattice. See section 4.3.3.5.1 for description of **Advanced** button options.

7.1.2. Running the Example and Viewing Output

After returning to the main Scoops3D-i window (fig. 7.1), the file can be checked for completeness and run in Scoops3D. To run the example in Scoops3D, select **Run** > **Run Scoops3D** from the main window menu bar. With this selection, Scoops3D-i automatically checks the input file for completeness before launching Scoops3D.

As Scoops3D executes, the command tool (Windows) or terminal (Macintosh) window displays the progress of the Scoops3D simulation, including the input file name, search node, search iteration number, percent completed of each search iteration, and number of trial surfaces analyzed (fig. 7.5). When the run is completed, "Successful execution …" with Scoops3D version number, date, and time are displayed in the window.

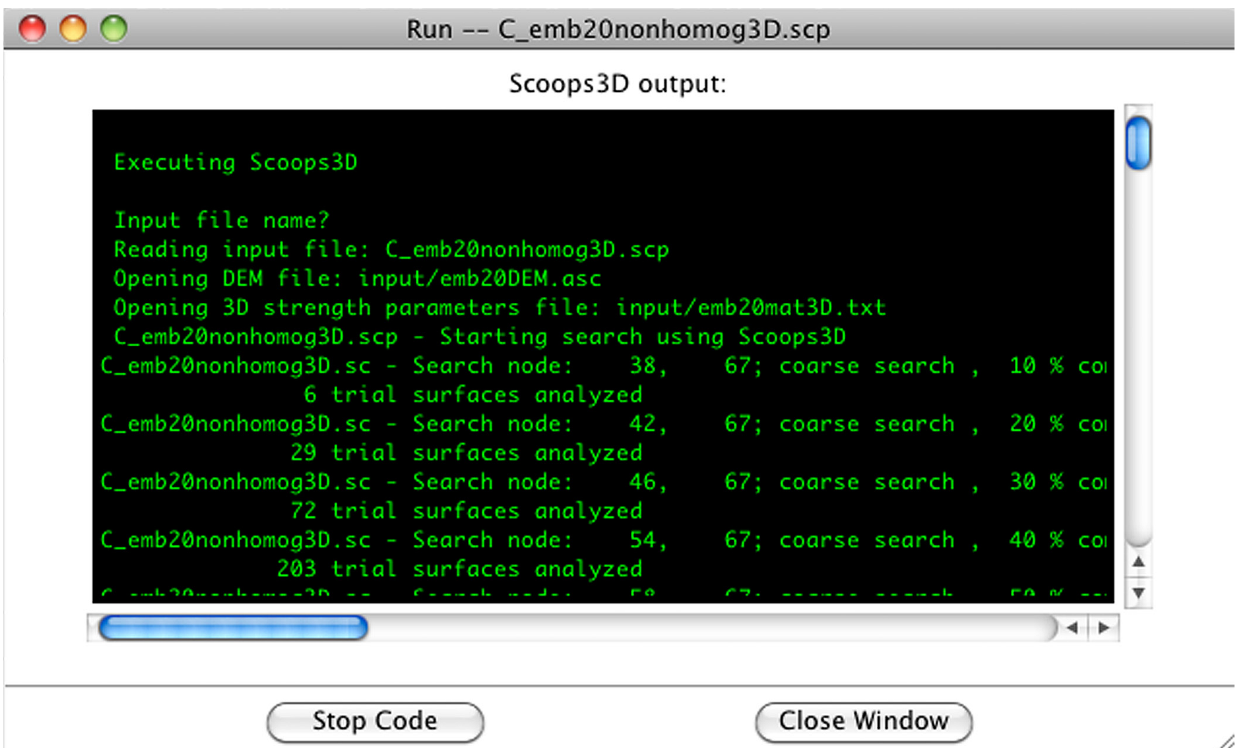
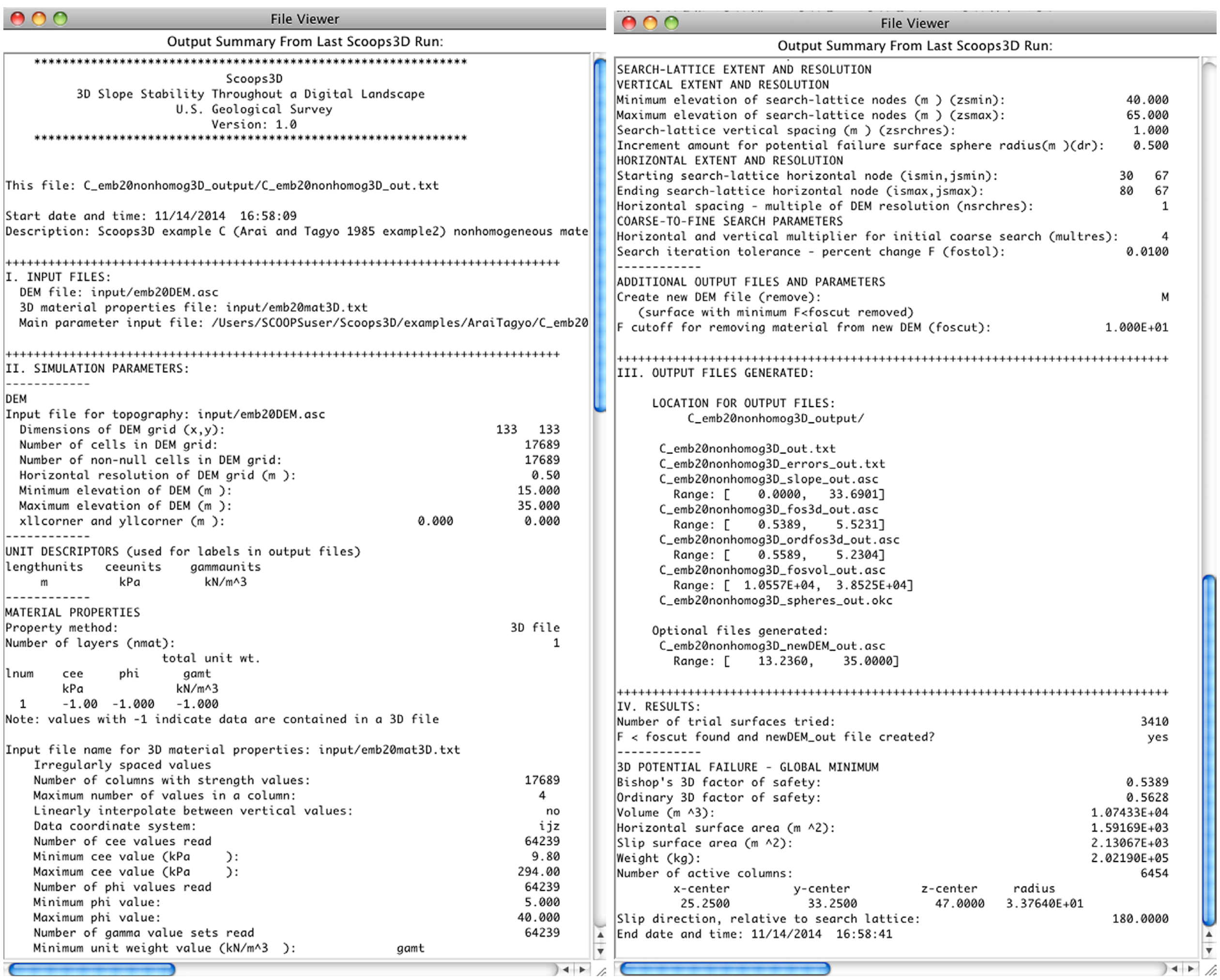


Figure 7.5. Screenshot of terminal window showing a Scoops3D run using example C. File name for example: *C_emb20nonhomog3D.scp*.

Upon successful execution of Scoops3D, output files for this example are placed in the subfolder labeled *C_emb20nonhomog3D _output*. The summary output file can be viewed using Scoops3D-i by selecting **View > Scoops3D Output File** from the main window menu bar. The file contents are displayed in a **File Viewer** window (fig. 7.6). Use the scroll bar to go to the bottom of this file, where information is shown about the global minimum *F* identified in this Scoops3D analysis in the section labeled “3D POTENTIAL FAILURE - GLOBAL MINIMUM” (fig. 7.6*B*). The least-stable surface (global minimum) identified in this Scoops3D analysis has a Bishop’s factor of safety of 0.5389 and a volume of 1.07433×10^4 m^3. Other details about the potential failure mass are provided in this section of the file. When finished viewing the contents, click the close button at the top of the **File Viewer** window.



```
File Viewer
Output Summary From Last Scoops3D Run:
    **************************************************************
                            Scoops3D
          3D Slope Stability Throughout a Digital Landscape
                       U.S. Geological Survey
                            Version: 1.0
    **************************************************************


This file: C_emb20nonhomog3D_output/C_emb20nonhomog3D_out.txt

Start date and time: 11/14/2014  16:58:09
Description: Scoops3D example C (Arai and Tagyo 1985 example2) nonhomogeneous mate

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
I. INPUT FILES:
  DEM file: input/emb20DEM.asc
  3D material properties file: input/emb20mat3D.txt
  Main parameter input file: /Users/SCOOPSuser/Scoops3D/examples/AraiTagyo/C_emb20

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
II. SIMULATION PARAMETERS:
------------
DEM
Input file for topography: input/emb20DEM.asc
  Dimensions of DEM grid (x,y):                                     133   133
  Number of cells in DEM grid:                                          17689
  Number of non-null cells in DEM grid:                                 17689
  Horizontal resolution of DEM grid (m ):                                0.50
  Minimum elevation of DEM (m ):                                       15.000
  Maximum elevation of DEM (m ):                                       35.000
  xllcorner and yllcorner (m ):                            0.000        0.000
------------
UNIT DESCRIPTORS (used for labels in output files)
lengthunits   ceeunits    gammaunits
     m          kPa          kN/m^3
------------
MATERIAL PROPERTIES
Property method:                                                      3D file
Number of layers (nmat):                                                    1
                      total unit wt.
lnum    cee     phi      gamt
        kPa             kN/m^3
  1     -1.00  -1.000   -1.000
Note: values with -1 indicate data are contained in a 3D file

Input file name for 3D material properties: input/emb20mat3D.txt
    Irregularly spaced values
    Number of columns with strength values:                             17689
    Maximum number of values in a column:                                   4
    Linearly interpolate between vertical values:                          no
    Data coordinate system:                                               ijz
    Number of cee values read                                           64239
    Minimum cee value (kPa     ):                                        9.80
    Maximum cee value (kPa     ):                                      294.00
    Number of phi values read                                           64239
    Minimum phi value:                                                  5.000
    Maximum phi value:                                                 40.000
    Number of gamma value sets read                                     64239
    Minimum unit weight value (kN/m^3  ):                  gamt
```

A

```
File Viewer
Output Summary From Last Scoops3D Run:
SEARCH-LATTICE EXTENT AND RESOLUTION
VERTICAL EXTENT AND RESOLUTION
Minimum elevation of search-lattice nodes (m ) (zsmin):                40.000
Maximum elevation of search-lattice nodes (m ) (zsmax):                65.000
Search-lattice vertical spacing (m ) (zsrchres):                        1.000
Increment amount for potential failure surface sphere radius(m )(dr):   0.500
HORIZONTAL EXTENT AND RESOLUTION
Starting search-lattice horizontal node (ismin,jsmin):                 30   67
Ending search-lattice horizontal node (ismax,jsmax):                   80   67
Horizontal spacing - multiple of DEM resolution (nsrchres):                 1
COARSE-TO-FINE SEARCH PARAMETERS
Horizontal and vertical multiplier for initial coarse search (multres):     4
Search iteration tolerance - percent change F (fostol):                0.0100
------------
ADDITIONAL OUTPUT FILES AND PARAMETERS
Create new DEM file (remove):                                               M
   (surface with minimum F<foscut removed)
F cutoff for removing material from new DEM (foscut):               1.000E+01

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
III. OUTPUT FILES GENERATED:

     LOCATION FOR OUTPUT FILES:
          C_emb20nonhomog3D_output/

      C_emb20nonhomog3D_out.txt
      C_emb20nonhomog3D_errors_out.txt
      C_emb20nonhomog3D_slope_out.asc
        Range: [    0.0000,    33.6901]
      C_emb20nonhomog3D_fos3d_out.asc
        Range: [    0.5389,     5.5231]
      C_emb20nonhomog3D_ordfos3d_out.asc
        Range: [    0.5589,     5.2304]
      C_emb20nonhomog3D_fosvol_out.asc
        Range: [  1.0557E+04,  3.8525E+04]
      C_emb20nonhomog3D_spheres_out.okc

     Optional files generated:
      C_emb20nonhomog3D_newDEM_out.asc
        Range: [    13.2360,    35.0000]

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
IV. RESULTS:
Number of trial surfaces tried:                                          3410
F < foscut found and newDEM_out file created?                             yes
------------
3D POTENTIAL FAILURE - GLOBAL MINIMUM
Bishop's 3D factor of safety:                                          0.5389
Ordinary 3D factor of safety:                                          0.5628
Volume (m ^3):                                                    1.07433E+04
Horizontal surface area (m ^2):                                   1.59169E+03
Slip surface area (m ^2):                                         2.13067E+03
Weight (kg):                                                      2.02190E+05
Number of active columns:                                                6454
        x-center         y-center         z-center     radius
         25.2500          33.2500          47.0000   3.37640E+01
Slip direction, relative to search lattice:                          180.0000
End date and time: 11/14/2014  16:58:41
```

B

Figure 7.6. Screenshots of summary output file created after successful completion of a Scoops3D run of example C. Output file name: *C_emb20nonhomog3D _out.txt* and input file name: *C_emb20nonhomog3D.scp*. *A*, Beginning lines contained in output file. *B*, Ending lines contained in output file.

Other Scoops3D output files can be viewed by selecting **View > ASCII Text File** and selecting the appropriate file from the navigation window. Many of these files are best viewed using a GIS or 2D or 3D visualization software (section 4.5).

The same procedure can be used to examine and run any of the examples listed in table 7.1. The user can identify examples of specific interest or open the files sequentially to become familiar with some of Scoops3D features and related files. Select **File > Open** to open another example, then open the **Subsurface Parameters** and **Search Configuration** windows and note how different scenarios require different input parameters and files. Several examples demonstrate the required files and file formats for complex scenarios (layer files, 3D subsurface properties, or 3D pore pressures).

7.2. Arai and Tagyo Embankment Configurations

The first set of examples uses a 20-m high embankment configuration with a 3:2 (33.7°) slope and material properties as described in section 6.3.3. We include five main parameter input files (examples A through E) that are 3D extensions of problems commonly used for verification of 2D slope stability software (Arai and Tagyo, 1985; Rocscience Inc., 2010; Feng and Fredlund, 2012). The five main parameter input files demonstrate: (A) homogeneous material properties, (B) non-homogeneous material properties with boundaries defined in layer files, (C) a 3D material property file, (D) a piezometric surface file, and (E) a 3D pressure head file (table 7.1).

These five examples are variations of the three scenarios defined in testing section 6.3.3 (table 6.14): homogeneous (Arai and Tagyo [1985], example 1), non-homogeneous (Arai and Tagyo [1985], example 2), and homogeneous with a piezometric surface (Arai and Tagyo [1985], example 3). The scenario with non-homogeneous material properties is used to demonstrate two different ways of describing non-homogeneous material properties in Scoops3D, requiring different input files: layer files (example B) or a 3D material property file with irregular vertical spacing (example C). These two approaches produce the same results. The homogeneous scenario with the addition of pore-water pressures defined as a piezometric surface is used to demonstrate two methods of describing the groundwater configuration: a piezometric surface file (example D) or a 3D pressure-head file (example E). Again, in this case both of these approaches produce the same results. For more explanation, see details of Scoops3D testing of 3D material property files and 3D pressure-head files in sections 6.5.1 and 6.5.2.

For examples A through E, the search is a special case of a box search wherein only a 2D cross section above the center of the embankment (minimum j = maximum j) is searched. This search is appropriate to identify a minimum factor of safety in symmetric topography such as an embankment; however, it will not provide a thorough search of a DEM that represents real-world topography.

There are five main parameter input files (described below) for the Arai and Tagyo embankment configurations, and tables 7.2 and 7.3 list the additional input files and their relation to the main parameter input files:

A_emb20.scp - homogeneous material properties (Arai and Tagyo [1985], example 1),
B_emb20nonhomog.scp - non-homogeneous material properties (Arai and Tagyo [1985], example 2), subsurface material properties are defined in the main parameter input file and elevations for the bottom of each material are defined in layer files,
C_emb20nonhomog3D.scp - non-homogeneous material properties (Arai and Tagyo [1985], example 2), subsurface material properties and elevations are defined in a 3D material properties file formatted for Scoops3D with ijz coordinates,
D_emb20wet.scp - homogeneous material properties with piezometric surface file (Arai and Tagyo [1985], example 3), and
E_emb20wet3D.scp - homogeneous material properties with piezometric surface (Arai and Tagyo [1985], example 3), described in a 3D pressure-head file formatted for Scoops3D with ijz coordinates.

Table 7.2. List of additional input files for Scoops3D examples A through E.

[These examples use a 20-m high, 3:2 embankment configuration (Arai and Tagyo, 1985). Files are contained in the *input* subfolder of the *AraiTagyo* folder. m, meter]

File name	File type	Description
emb20DEM.asc	Grid	Ground-surface elevations (DEM), 20 m high embankment with 3:2 slope
emb20layer_1.asc	Grid	Bottom elevation of layer 1
emb20layer_2.asc	Grid	Bottom elevation of layer 2
emb20mat3D.txt	3D	3D material property file defining the material properties equivalent to the layer files (ijz coordinates, see section 4.4.2.2.1).
emb20piezo.asc	Grid	Elevation of the piezometric surface
emb20phead3D.txt	3D	3D pressure head file defining a piezometric surface below each DEM cell (ijz coordinates, see section 4.4.2.2.1)

Table 7.3. Relation between main parameter input files and additional Scoops3D input files needed for Scoops3D examples A through E.

[Main parameter (.scp) files are contained in the *AraiTagyo* folder and the additional files are contained in the *input* subfolder]

	emb20DEM.asc	*emb20layer_1.asc*	*emb20layer_2.asc*	*emb20mat3D.txt*	*emb20piezo.asc*	*emb20phead3D.txt*
A_emb20.scp	x					
B_emb20nonhomog.scp	x	x	x			
C_emb20nonhomog3D.scp	x			x		
D_emb20wet.scp	x				x	
E_emb20wet3D.scp	x					x

7.3. Donald and Giam Embankment Configurations

Our second set of examples uses a configuration that is also a 3D extension of examples often used for verification of 2D slope stability software (Donald and Giam, 1995; Rocscience Inc., 2010; Feng and Fredlund, 2012). Examples F through J use a 10-m high embankment with a 2:1 (26.6°) slope and material properties as described in section 6.3.2. The five main parameter input files demonstrate: (F) homogenous material properties, (G) homogenous material properties with a single trial surface, (H) non-homogenous material properties with boundaries defined in layer files, (I) a 3D material property file, and (J) seismic loading (table 7.1).

The five Scoops3D input files include variations of the three scenarios defined in section 6.3.2 (table 6.11): homogeneous (Scoops3D examples F and G; Donald and Giam [1995] example 1a), non-homogeneous (Scoops3D examples H and I, Donald and Giam [1995] example 1c), and non-homogeneous with seismic loading (Scoops3D example J; Donald and Giam [1995] example 1d). With the exception of one single trial surface analysis (example G), the search method for these files is a special case of a box search with a 2D cross section above the center of the embankment. For a more detailed explanation of this type of search, see the Arai and Tagyo embankment configurations (section 7.2).

Two examples have main parameter input files with a simple homogeneous scenario and illustrate two methods of analysis: one uses a search lattice with a special case of a box search defining a 2D cross section (example F), and one uses a single trial surface (example G). This single surface is the global minimum from the search of the 2D cross section in example F.

Two other examples have main parameter input files and non-homogeneous material properties to demonstrate different methods of describing non-homogeneous properties in Scoops3D: one uses layer files (example H) and one uses a 3D material property file with irregular vertical spacing in ijz coordinates (example I). The 3D file for example I mimics the material distribution contained in the layer files of example H. The final example, J, uses non-homogeneous material properties with the addition of seismic loading.

There are five main parameter input files for the Donald and Giam embankment configurations (described below); tables 7.4 and 7.5 describe the additional input files and their relation to each of the main parameter input files:

F_emb10.scp - homogeneous material properties (Donald and Giam [1995], example 1a),

G_emb10single.scp - homogeneous material properties (Donald and Giam [1995], example 1a), search method is a single surface identified as the global minimum from example F,

H_emb10nonhomog.scp - non-homogeneous material properties (Donald and Giam [1995], example 1c), subsurface material properties are defined in the main parameter input file, and elevations for the bottom of each material are defined in layer files,

I_emb10nonhomog3D.scp - non-homogeneous material properties (Donald and Giam [1995], example 1c), subsurface material properties and elevations are defined in a 3D material properties file formatted for Scoops3D with ijz coordinates, and

J_emb10nonhomogeq.scp - non-homogeneous material properties (Donald and Giam [1995], example 1c), subsurface material properties are defined in the main parameter input file, elevations for the bottom of each material are defined in layer files with addition of horizontal seismic loading (Donald and Giam [1995], example 1d).

Table 7.4. List of additional input files for Scoops3D examples F through J.

[Examples use a 10-m high, 2:1 embankment configuration (Donald and Giam, 1995). Files are contained in the *input* subfolder of the *DonaldGiam* folder]

File name	File type	Description
emb10DEM.asc	Grid	Ground-surface elevations (DEM), 10 m high embankment with 2:1 slope
emb10layer_1.asc	Grid	Bottom elevation of layer 1
emb10layer_2.asc	Grid	Bottom elevation of layer 2
emb10mat3D.txt	3D	3D material property file defining the material properties equivalent to the layer files (ijz coordinates, see section 4.4.2.2.1).

Table 7.5. Relation between main parameter input files and additional Scoops3D input files needed for Scoops3D examples F through J.

[Main parameter (.scp) files are contained in the *DonaldGiam* folder and the additional files are contained in the *input* subfolder]

	emb10DEM.asc	*emb10layer_1.asc*	*emb10layer_2.asc*	*emb10mat3D.txt*
F_emb10.scp	x			
G_emb10single.scp	x			
H_emb10nonhomog.scp	x	x	x	
I_emb10nonhomog3D.scp	x			x
J_emb10nonhomogeq.scp	x	x	x	

7.4. Symmetric Cone Configurations

These five examples use main parameter input files (examples K through O) with a 1000-m high cone having a 30° slope and a wide range of material strengths, as presented in section 6.2.2. The examples illustrate three different sets of values for homogeneous material properties, two types of searches, and the use of a groundwater configuration described by a pore-pressure ratio, r_u (table 7.6).

These examples demonstrate how the parameters for a thorough search can vary depending on the λ value (equation 5.1) of the material properties (sections 5.3.1 and 5.3.5). The examples use three different combinations of material properties listed in table 6.5; relatively high cohesive strength or high λ (example K; λ = 1.0), intermediate λ (examples L, N, O; λ = 0.125), and low λ (example M; λ = 0.025) (table 7.6).

Table 7.6. Summary of main parameter input files for cone configurations with different values of λ (Scoops3D examples K through O).

[Input files are contained in the *cone* folder. m, meter]

Example	Main parameter input file	λ	Groundwater configuration	Full DEM search	Vertical extent of search lattice (m) (***zsmin, zsmax***)	Volume criteria (***vmin, vmax***) (m³)
K	*K_conehi.scp*	1.00	None	No	1,000–2,000	1×10^7 m^3 – 1×10^{10}
L	*L_conemed.scp*	0.125	None	No	1,200–2,200	1×10^6 m^3 – 1×10^9
M	*M_conelo.scp*	0.025	None	No	1,900–2,800	1×10^6 m^3 – 1×10^9
N	*N_conemedfullsearch.scp*	0.125	None	Yes	1,200–2,200	1×10^6 m^3 – 1×10^9
O	*O_conemedru.scp*	0.125	Pore-pressure ratio, r_u	No	1,200–2,200	1×10^6 m^3 – 1×10^9

For the scenario with the lowest λ (cohesive strength is low relative to frictional strength), we expect a smaller, shallower trial surface for the global minimum (example M). Thus, the rotational center for this minimum surface will be located at a relatively high elevation compared to the scenarios with larger values of λ, and example M has a higher vertical extent for its search lattice (table 7.6). Likewise, example M, with lower λ, uses smaller minimum and maximum volume limits for its search. In contrast, example K has a higher λ value with higher minimum and maximum volume limits. The difference in search parameters can be seen by comparing the two files *K_cone30hi.scp* and *M_cone30lo.scp*. The files may be viewed side by side in a text editor, or by opening the **Search Configuration** window in Scoops3D-i for each .scp file. Determination of the optimal search values is usually found by trial and error, but tips for performing an optimal search are contained in chapter 5.

We provide two variations of a box search for the intermediate λ value examples: a search of a 2D cross section above the center of the cone (example L) and a more thorough search of the full cone-shaped DEM (example N). The first search is designed to identify the global minimum F in symmetric topography, whereas the second search will identify the minimum F for every DEM cell but requires more computational time. For a more detailed explanation of the cross-section search, see the Arai and Tagyo embankment in section 7.2. Our final variation using intermediate λ (example O) demonstrates the addition of pore-water pressure effects using a pore-pressure ratio, r_u.

There are five main parameter input files for these cone examples, as summarized below. All configurations use a 1,000-m high cone DEM with a 30° slope (*cone1000DEM.asc*). Note that the vertical extent of the searches and the volume limits vary depending on λ. There are no additional input files.

K_conehi.scp - λ = 1.0, search for global minimum F using 2D cross section, vertical extent of search lattice ranges from 1,000 to 2,000 m, volume limits range from 1×10^7 m^3 to 1×10^{10} m^3,

L_conemed.scp - λ = 0.125, search for global minimum F using 2D cross section, vertical extent of search lattice ranges from 1,200 to 2,200 m, volume limits range from 1×10^6 m^3 to 1×10^9 m^3,

M_conelo.scp - λ = 0.025, search for global minimum F using 2D cross section, vertical extent of search lattice ranges from 1,900 to 2,800 m, volume limits range from 1×10^6 m^3 to 1×10^9 m^3,

N_conemedfullsearch.scp - λ = 0.125, thorough search of entire DEM, and

O_conemedru.scp - λ = 0.125, r_u = 0.2, search for global minimum F using 2D cross section, vertical extent of search lattice ranges from 1,200 to 2,200 m, volume limits range from 1×10^6 m^3 to 1×10^9 m^3.

7.5. Seattle DEM Examples

We provide two examples (P and Q) that illustrate the use of stratigraphic layers for the Duwamish Head region of southwestern Seattle, Washington, with and without 3D pore-pressure head data. The stratigraphic layers represent a 3D geologic model (Brien and Reid, 2007; 2008) derived from geologic mapping of the region (Troost and others, 2005). The groundwater configuration is derived from a 3D groundwater flow simulation using the model, MODFLOW-2000 (Harbaugh and others, 2000). The output from this groundwater flow model was interpreted to create a 3D pressure-head file for Scoops3D (Brien and Reid, 2007; 2008). Input files for these examples include a 10-ft resolution DEM, layer files, a 3D pressure-head file, and a search file to limit the horizontal extent of the initial coarse search lattice.

The examples contain two scenarios: non-homogeneous material properties using layer files with no groundwater (example P) and the same case with a groundwater configuration defined in a 3D pressure head file (example Q). In both scenarios the area of interest is the steep coastal bluffs, and therefore the horizontal search extent is limited in two ways: (1) the DEM is clipped from the original rectangular DEM to include only the area of interest, and (2) the initial coarse search is limited by a search file that restricts the search space to the area of interest.

There are two main parameter input files for the Seattle scenarios (summarized below); tables 7.7 and 7.8 describe the additional input files and their relation to the main parameter input files:

P_seadry.scp – non-homogeneous material properties, subsurface material properties are defined in the main parameter input file; elevations for the bottom of each material are defined in layer files; initial coarse search is restricted by a search file and

Q_seawet.scp – non-homogeneous material properties, subsurface material properties are defined in the main parameter input file; elevations for the bottom of each material are defined in layer files; groundwater configuration is specified in a 3D pressure-head file; initial coarse search is restricted by a search file.

Table 7.7. List of additional input files for the Scoops3D Seattle examples P and Q.

[Files are contained in the *input* subfolder of the *Seattle* folder. The .prj file provides coordinate system information for the user, but is not used by Scoops3D]

File name	File type	Description
seaclipDEM.asc	Grid	Ground-surface elevations (DEM), southwest Seattle (clipped to region of interest)
seaclipDEM.prj	Text	Coordinate system and projection information for DEM
sealayer_1.asc	Grid	Bottom elevation of layer 1
sealayer_2.asc	Grid	Bottom elevation of layer 2
sealayer_3.asc	Grid	Bottom elevation of layer 3
seaphead3D.txt	3D	3D pressure-head file
seasearch.asc	Grid	Horizontal locations for initial coarse search-lattice nodes

Table 7.8. Relation between main parameter input files and additional Scoops3D input files needed for Scoops3D Seattle examples P and Q.

[Files are contained in the *input* subfolder of the *Seattle* folder]

	seaclipDEM.asc	*sealayer_1.asc*	*sealayer_2.asc*	*sealayer_3.asc*	*seaphead3D.txt*	*seasearch.asc*
P_seadry.scp	x	x	x	x		x
Q_seawet.scp	x	x	x	x	x	x

7.6. Mount St. Helens DEM Example

We also include an example (R) that uses a real-world DEM for Mount St. Helens, Washington, prior to the May 18, 1980, collapse and eruption. The DEM represents the topography of the deformed volcano edifice (bulge on north flank) as it existed a few days prior to its catastrophic collapse (see Reid and others [2000] for details). Deformed topography is based on topographic contours derived from aerial photographs taken on May 12, 1980. The example configuration uses homogeneous material properties with no groundwater. Output files from this example are used for illustration in section 4.5.1.

This example demonstrates the advantages of resampling the original DEM to a coarser resolution to reduce runtime. Whereas the original 30-m DEM provides higher resolution topography, it is unnecessary to use topography with this level of detail to search for large (0.10 to 3.5 km^3) potential failure masses. To reduce computer memory requirements and runtime, and still provide a sufficient number of columns for accurate computation of factors of safety and volumes, we resampled the 30-m DEM to 100 m using the ArcMap toolbox resample tool with cubic convolution option (http://www.esri.com/software/arcgis). Both DEMs are provided in the *input* subfolder of this example for comparison and their names are listed in table 7.9. There is one main parameter input file for the St. Helens example:

R_sthel.scp - homogeneous material properties, search parameters optimized for a balance between good solution quality and faster runtime, uses the 100-m resolution DEM (file name: *sthel_res100mDEM.asc*).

Table 7.9. List of different resolution DEMs of the Mount St. Helens edifice showing north flank deformation prior to the 1980 collapse.

[Files are contained in the *input* subfolder of the *StHelens* folder. The 100-m DEM is used in example R. The .prj file provides coordinate system information for the user, but is not used by Scoops3D]

File name	File type	Description
sthel_res30mDEM.asc	Grid	Ground-surface elevations (DEM), Mount St. Helens, 30-m resolution
sthel_res100mDEM.asc	Grid	Ground-surface elevations (DEM), Mount St. Helens, 100-m resolution
sthelDEM.prj	Text	Coordinate system and projection information for DEM

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Glossary of Selected Terms

Active column: A column (full or partial) that is used for the computation of volume, area, and factor of safety, *F*, of a potential failure mass. Full columns include all four corners of a digital elevation model (DEM) cell whereas partial columns, located around the edges of the potential failure mass, include two or three corner nodes. (See section 2.1).

Critical node, or ***critical lattice node***: A point in the three-dimensional (3D) search lattice that defines the rotational center of the critical surface for a given DEM cell. (See section 3.2.2).

Critical size (volume or area): Size of the potential failure mass associated with a given critical surface. Critical size is specified in units of either volume or horizontal area depending on the user-specified primary size criterion. (See section 3.2).

Critical surface, or ***critical trial surface***: The trial surface with the lowest factor of safety, *F*, for a given DEM cell. A DEM that has been thoroughly searched will be affected by many critical surfaces. (See section 3.2).

Global minimum F: Factor of safety, *F*, for the least-stable (lowest value of *F*) critical surface found during a Scoops3D search. (See section 3.2).

Overall fall direction: Azimuthal direction defined by the average ground-surface slope of all full columns contained within a potential failure mass. Scoops3D always computes a factor of safety for potential slip in this direction. The user may specify other potential slip directions relative to the overall fall direction. (See sections 2.1 and 4.4.1.1.9.1).

Parameter-line pair or ***line pair***: Data input structure in the main parameter input file for Scoops3D. The first line of each line pair contains descriptor text; the first word of this line is the parameter-line ID. The second line of each pair contains the data. Both lines must be present for valid input. (See section 4.4.1).

Potential failure mass: The predefined mass used for calculating factor of safety, *F*, in a limit-equilibrium slope-stability analysis. In Scoops3D, a potential failure mass is composed of the 3D columns (both full and partial) above a trial surface and beneath the DEM surface. For a given search, potential failure masses must have sizes (volume and [or] area) within user-specified limits. (See sections 2.1 and 4.4.1.1.10).

Rotational center: Location of the center of a sphere (above a DEM) used to create a trial surface underlying a DEM. A given sphere may intersect the DEM in multiple locations, thereby creating multiple trial surfaces. Each rotational center may be used to form multiple spheres of different radii. Typically, rotational centers are located at nodes within a search lattice. Note that Scoops3D computes moment equilibrium of a potential failure mass that rotates around a horizontal axis through the rotational center. (See sections 2.3 and 3.2).

Search lattice: Orthogonal 3D array of rotational center nodes (points) located above a DEM. Each node is centered above a DEM cell and typically represents the rotational center for multiple trial surfaces. Horizontal and vertical lattice-node spacing is specified by the user. Scoops3D assesses the stability of all parts of a DEM by systematically analyzing the slope stability of trial surfaces created at each node in the search lattice. (See sections 3.2 and 4.4.1.1.9).

Trial surface, or ***trial slip surface***: The predefined potential failure or slip surface used for calculating factor of safety, *F*, in a limit-equilibrium slope-stability analysis. Scoops3D uses trial surfaces composed of parts of a sphere defined by a rotational center, and assumes rotational slip. (See chapter 2 and section 4.4.1.1.9).

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