LANDSLIDES OF THE CINCINNATI, OHIO, AREA

Anchoring of Thin Colluvium by Roots of Sugar Maple and White Ash on Hillslopes in Cincinnati

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Anchoring of Thin Colluvium by Roots of Sugar Maple and White Ash On Hillslopes in Cincinnati

By MARY M. RIESTENBERG

LANDSLIDES OF THE CINCINNATI, OHIO, AREA

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Studies of root morphology, distribution, and pull-out resistance show how tree roots help stabilize thin colluvium

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Anchoring of Thin Colluvium by Roots of Sugar Maple and White Ash on Hillslopes in Cincinnati

By Mary M. Riestenberg[1]

ABSTRACT

Tree roots effectively anchor colluvium as much as 1 m thick on steep hillslopes bordering the Ohio River and its tributaries in the Cincinnati, Ohio, area. This ability is demonstrated through detailed analyses of shallow landslides on forested hillslopes and through studies of the morphology, distribution, and pull-out resistance of roots of two species of trees that dominate the forests. The roots penetrate the clay colluvium, cross shear zones, and anchor the colluvium to the underlying weathered limestone and shale bedrock.

The extent to which a tree species can anchor colluvium and stabilize a hillslope depends on the morphology of its root system. A small (8–16 cm diameter) sugar maple characteristically has a well-developed lateral root system, but no dominant taproot. It can stabilize surficial soil, but its shallow root system cannot stabilize colluvium thicker than 0.5 m. A white ash of similar diameter has well-developed shallow roots and a stout, deeply penetrating taproot. It can stabilize soil as much as 1 m thick.

Stability analyses indicate that small white ash trees may be widely spaced and still stabilize a hillslope. For instance, white ash as much as 7 m apart will anchor a 43 cm thickness of colluvium on a 30° hillslope.

INTRODUCTION

Previous laboratory studies have shown that roots increase the shear strength of soil, but have failed to demonstrate how roots affect the strength of soil in place on hillslopes. This study investigates the interaction of roots and landslide shear surfaces and quantifies the resulting enhancement of soil shear strength.

Tree roots increase both the tensile and shear strength of soil. The addition of tree roots to soil increases its tensile strength from three to five times (Kaul, 1965; Endo and Tsuruta, 1969a); the shear strength of the soil increases with increasing mass of roots per unit volume of soil (Endo and Tsuruta, 1969a; O'Loughlin, 1972; Ziemer, 1981). Endo and Tsuruta (1969b), Gray (1974, 1978), Waldron (1977), and Wu (1984) contend that roots increase shear strength by increasing the cohesion of the soil. The increase in cohesion of rooted soil ranges from one to 20 kilopascals (O'Loughlin and Ziemer, 1982), and the cohesion increases with increasing cross-sectional area of roots per area of the shear surface (Waldron, 1977; Wu and others, 1979; Waldron and others, 1983; Wu, 1984).

Measurements of shear strength demonstrate that both peak and residual strengths of the soil are increased by the presence of roots (Manbeian, 1973) and that rooted soil can be deformed by shear to a greater extent than fallow soil before it fails (Kaul, 1965). Rooted soil not only has a higher peak shear strength than fallow soil, but it also accommodates greater displacement before reaching its peak shear strength. Waldron and others (1983) demonstrated that the shear strength peaks at 18 mm displacement in soils with alfalfa and pine roots.

A few studies have been made of the anchoring capacity of roots. Fraser (1962) studied windthrow and the associated forces required to pull out spruce and fir trees, and determined that the force necessary to pull out a tree increases with loading rate. The pull-out resistance increases with root size and with the maturity of the root system, and decreases if the roots are diseased (Ortman and others, 1968) or have begun to decay (Kitamura and Namba, 1968).

In a previous study of the contribution of roots to hillslope stability, Riestenberg and Sovonick-Dunford (1983) concluded that roots contributed 85 percent of the shearing resistance at the base of a shallow landslide, and the soil contributed the remaining 15 percent. However, I have reexamined many of the assumptions used in our previous study and found them inconsistent with my more recent field observations and the laboratory measurements of others. In particular, Riestenberg and Sovonick-Dunford (1983) assumed that all roots break simultaneously and that

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the full tensile strength of each root was mobilized parallel to the shear surface. However, my observations indicate that many of the roots were pulled out of the materials underlying the shear surface and failed at less than their full tensile strength. My field experiments indicate that root pull-out resistance is mobilized gradually and that roots fail at different amounts of displacement, depending on their morphologies. Laboratory experiments (Fleming and Johnson, 1994) also indicate that shear strength of the colluvium is much higher than previously estimated (Fleming and others, 1981; Riestenberg and Sovonick-Dunford, 1983).

This paper presents evidence that roots, like artificial ground anchors (Hanna, 1982), are pulled from the colluvial soil by landsliding. These observations are then supported by pull-out tests on roots exposed in excavations and by tensile tests on excised roots. Next the paper describes the morphology and distribution of the roots of sugar maple and white ash, species which co-dominate the hillslopes. Lastly, data on the pull-out resistance of roots, root distribution and morphology, soil strength, and thickness of colluvium are combined in stability analyses to determine the effects of tree spacing and colluvium thickness on the stability of wooded hillslopes.

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ROOTS ACT AS SOIL ANCHORS

There is overwhelming evidence that roots act as soil anchors, transmitting tensile forces across a discontinuity, the shear surface, to the underlying bedrock. A detailed field study at the Delhi landslide (fig. 1) indicates that roots become stretched along surfaces during soil failure. Observations indicate that they are pulled from the soil or fail in tension, as would flexible cables or ground anchors (Hanna, 1982), rather than fail in shear.

Roots penetrating the basal shear surface of the Delhi Pike landslide (fig. 1; see Fleming and Johnson, 1994, for a complete description) have been moved and realigned by a few centimeters of landslide movement. Figure 2*A* shows about 70 roots penetrating the basal shear surface of the landslide. The roots are clustered in groups where they penetrate the shear surface through fissures. Above and below the shear surface the roots are nearly perpendicular to the shear surface. At the shear surface, centimeters-long segments of the roots are aligned parallel with striations that indicate the direction of sliding (fig. 2*B*). Similar realignment of a root that penetrates five shear surfaces is shown in figure 3. Figure 4 also shows closeup views of roots that have been deformed and reoriented parallel with the striations on the shear surface.

Deformation and reorientation of the roots parallel with the striations in the failure surface indicate that the roots are pulled out of the soil during sliding. Above and below the shear surface, the roots appear to have maintained their original, relatively random orientations as they became deformed near the shear surface. Roots grow in length only at their tips (Kramer and Kozlowski, 1979), so the deformed segments must have been pulled into the plane of the shear surface from their original positions above or below it. Moreover, the thin layer of remolded colluvium that surrounds the root shown in figure 3 also suggests that the root was pulled lengthwise through its own hole in the colluvium.

Additional evidence that roots are pulled from the soil during sliding was observed at the Rapid Run landslide (fig. 1; see Riestenberg and Sovonick-Dunford, 1983, for a complete description). The slope failed as a series of blocks or slide elements, each supporting a segment of the maple-dominated forest. Each slide element was bounded by scarps draped with roots. Many of the roots had broken in tension, but many others were pulled out of the colluvium intact. Furthermore, lengths of the roots varied, indicating that the roots probably had failed after varying amounts of soil displacement.

MEASUREMENT OF PULL-OUT RESISTANCE OF TREE ROOTS

I verified the notion that roots act as anchors by measuring the pull-out resistance of roots exposed in excavations and comparing it to the laboratory-measured tensile strength of roots. After briefly describing the methods I used for these measurements I will summarize the results.

The pull-out resistance of the roots of sugar maple (*Acer saccharum* M.) and white ash (*Fraxinus americana* L.), two dominant species on Cincinnati's hillslopes, was measured in excavations dug by a Vermeer spade at the Spring Grove site (fig. 1). The site is forested, slopes gently,

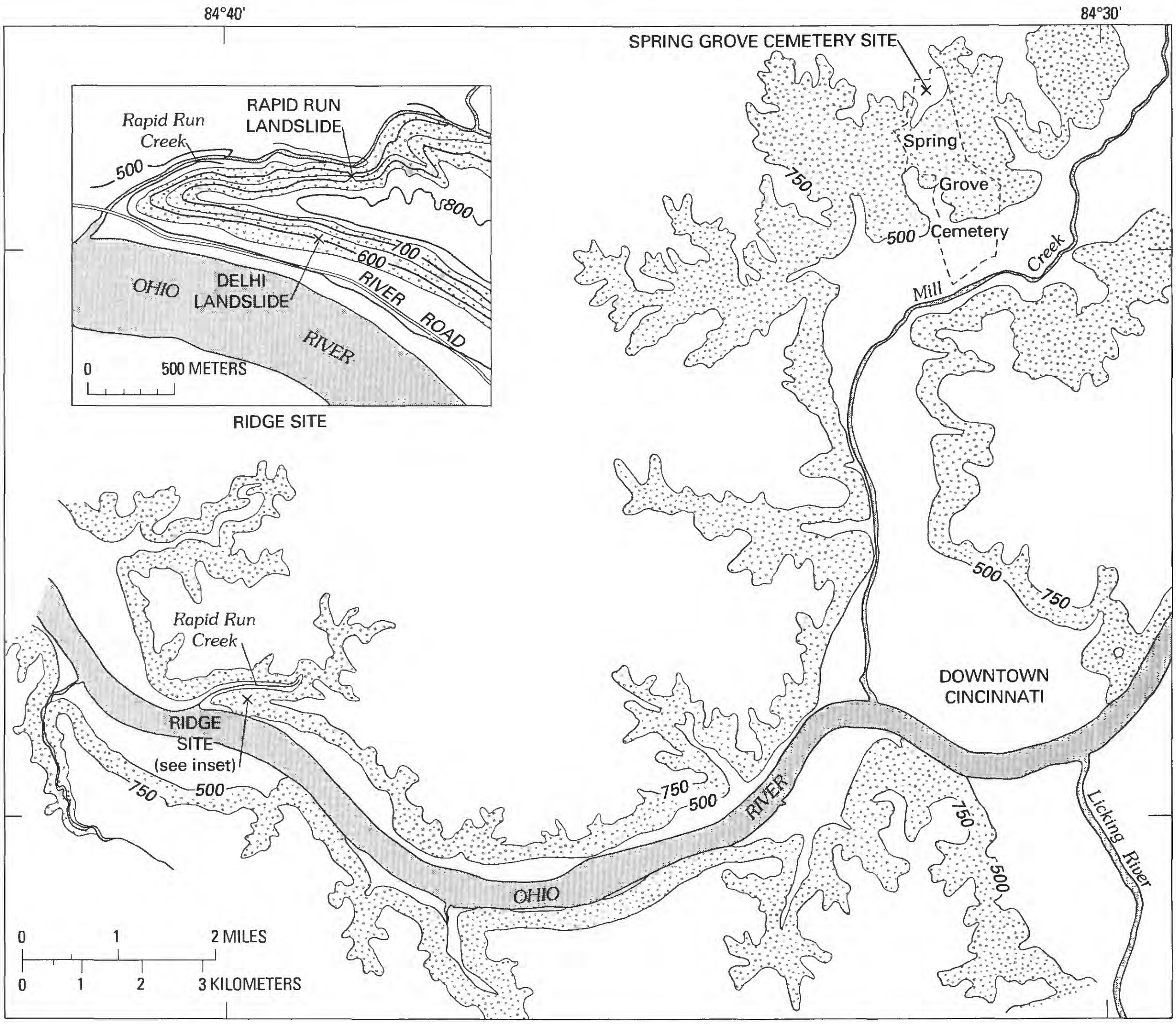


Figure 1. Location of the two study sites and river bluffs. Contours in inset show elevation in feet. The bluffs along the Ohio River and its tributaries, indicated by stippling in the illustration, are forested and contain many shallow, planar landslides. The failures occur at the interface of the colluvium and the weathered bedrock. Tree roots penetrate the failure surfaces and are involved in the shallow landslides. The ridge near the Ohio River is the site of both the Delhi and Rapid Run landslides. The Spring Grove site is on a gently sloping, upland part of Cincinnati. All these sites are underlain by the same type of colluvium soil and support forests dominated by sugar maple and white ash.

and is underlain by the silty clay colluvium described as Eden soil by Lerch and others (1982), the same soil that underlies the ridge site. The Vermeer spade is a truck-mounted, four-bladed hydraulic spade, which can remove a small tree, complete with the soil surrounding its central root system. It is used by nurseries for removal and transplanting of saplings (fig. 5). This type of excavation was useful for this study because the Vermeer spade severs roots at a specified distance from the tree and cuts them cleanly, with little or no tearing. The spade cuts a conical soil face about a tree, exposing the three-dimensional root distribution. The cut is 1.1 m in diameter at the ground surface and comes to a point approximately 0.85 m below the ground surface.

The colluvium at the Spring Grove test sites was kept as moist as possible by daily watering throughout the test period (May through July) in an effort to reproduce the soil moisture conditions of winter and spring, when shallow landslides in Cincinnati are usually active.

Trees with diameters ranging from 8 to 16 cm were tagged and excavated. The colluvium outside the conical excavations was mapped, and the roots exposed at the surface labeled with a tag listing species, tree number, and individual root number. Measurements of the diameters of the roots projecting from the excavation face, their depth, and their orientations were also recorded. Bark was removed from the exposed ends of the roots to prepare

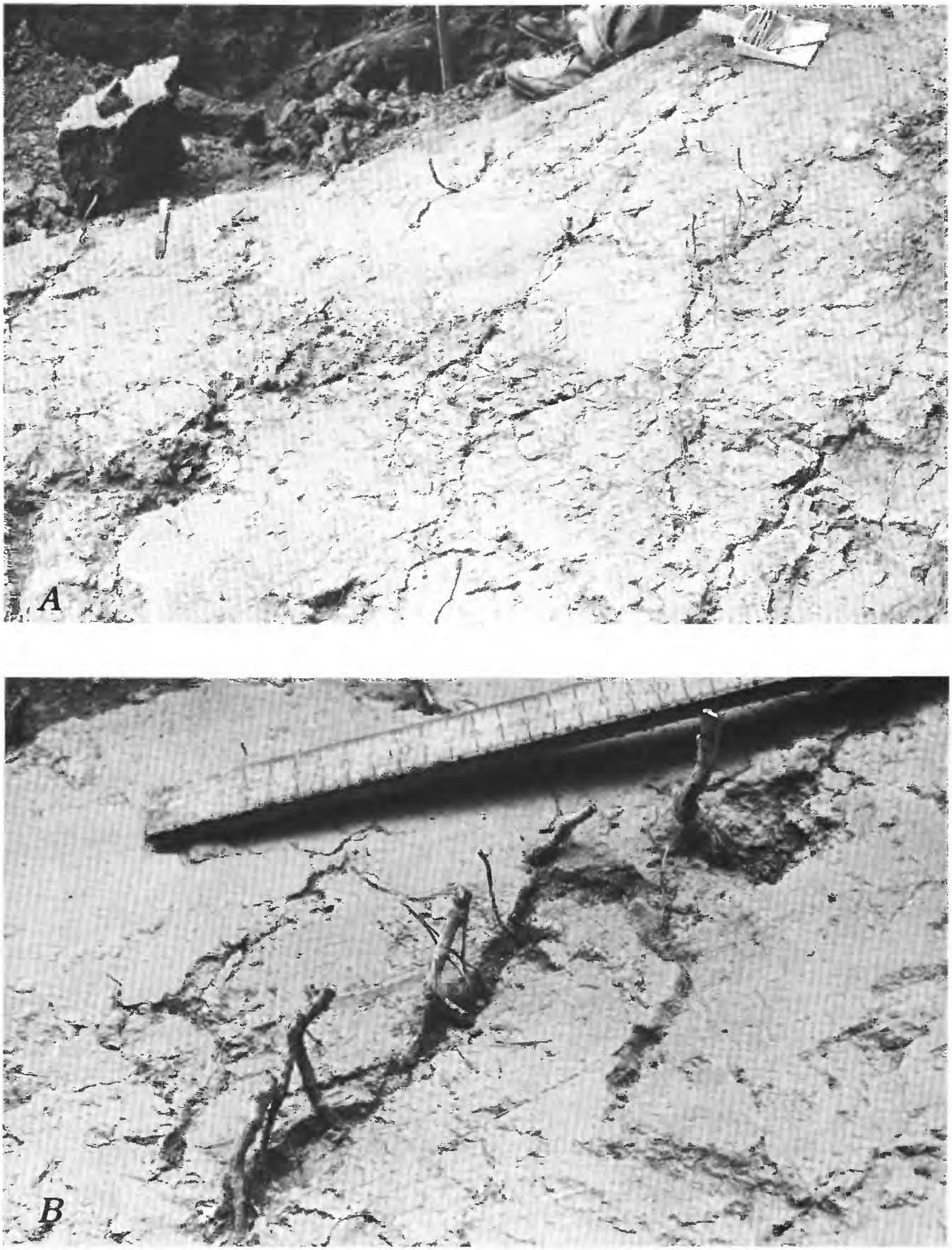


Figure 2. Roots penetrating the shear surface of a shallow, planar landslide. *A*, The surface, measuring 2.53 m^2 in area, is exposed at 1 m below the ground surface. Seventy roots project through the shear surface. *B*, Roots are reoriented at the shear surface in the direction of landslide movement. (Tape measure calibrated in centimeters.)

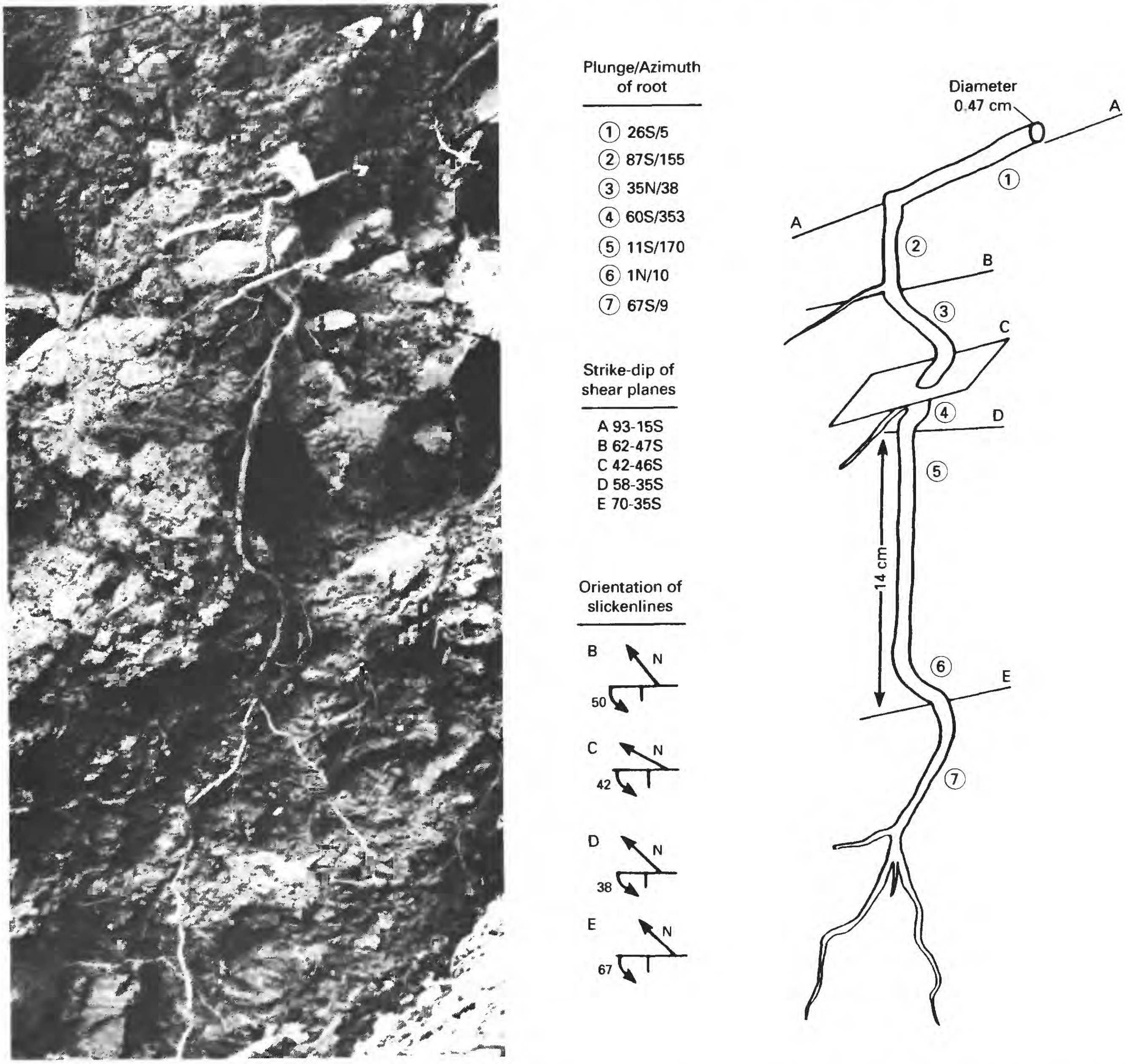


Figure 3. A root deformed along five shear surfaces in a zone of anastomosing surfaces near the landslide toe. The 28-cm long, deformed root follows a tortuous path through a film of remolded colluvial soil. The colluvium outside the film exhibits little evidence of deformation. The deformation of the root is controlled by the positions of the shear surfaces and the direction of displacement. The root is realigned on each shear surface in the direction of shear as indicated by striations on the shear surface.

them for gripping with bias-woven, steel cable pullers as part of the pull-out test described below.

A boat winch of 5.3 kilonewtons capacity was modified to pull out the roots (fig. 6*A*). The hand-operated winch was anchored, and its load cable attached to the root by a cable puller. In some tests a pulley was used to increase the mechanical advantage. The cable was threaded through a pulley supported by a beam to eliminate friction and to accommodate alignments of the cable (fig. 6*B*).

For every root pulled, the following parameters were measured or observed:

1. Diameter of root at soil face.
2. Diameters of all truncated ends.
3. Length of root from cut end at excavation face to largest truncated terminus.
4. Order of root pulled, with the first-order roots being smallest (that is, having no smaller roots branching off them) and second-order roots being those from which first-order roots branch, and so on.
5. Depth of root in the colluvium at face of excavation.
6. Azimuth and plunge of root.

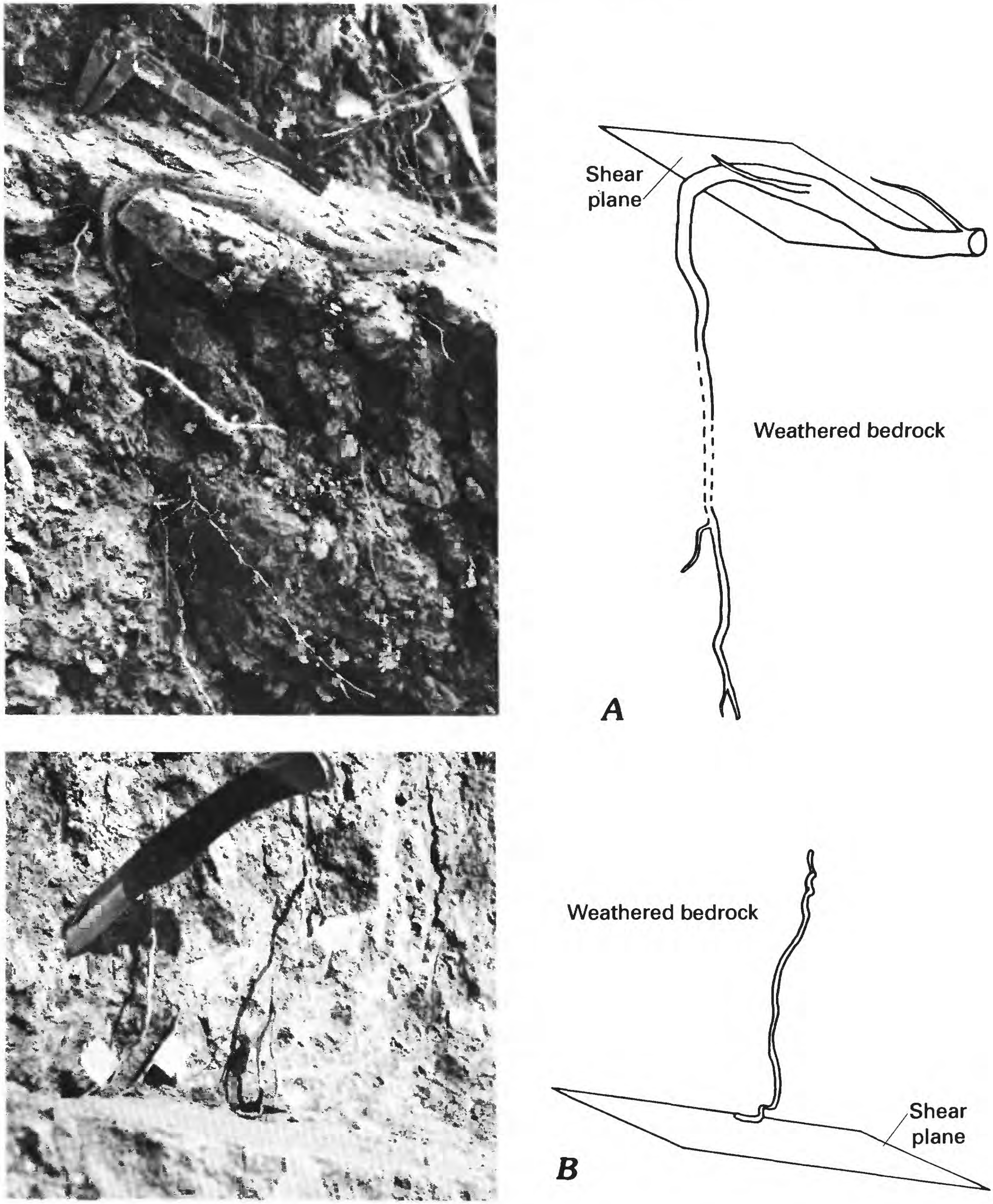


Figure 4. Two deformed roots exposed at the excavated shear surface. The roots are pulled out of their preslide position and realigned at the shear surface during landsliding. *A*, The root is realigned in the direction of shear at the shear surface. The root is deformed more than 90° from its orientation below the surface. *B*, The root is realigned from its orientation below the shear surface in the direction of shear at the failure surface. It is abruptly deformed again above the surface at an angle approaching 90° from its orientation at the surface.

Figure 5. The Vermeer spade used to expose the roots of some of the trees. The hydraulically driven spade removes a cleanly cut cone of roots from the colluvium, allowing subsequent study of root characteristics. It also exposes truncated roots on the conical trench face for measurement of pull-out resistance.

7. Species of root. Sugar maple and ash sometimes protruded from the same soil face but were easy to distinguish from each other; the ash has a distinctive thick, pale-gray-brown bark, and is ring porous, whereas the sugar maple has a deep brown bark, underlain by a red phloem layer, and is diffuse porous.

Graphs relating load, displacement, and time were constructed for each root removed from the colluvium.

The pull-out resistance of the maple and ash roots was compared to their tensile strength, which was measured in the laboratory using a testing machine with a capacity of 22 kilonewtons. Fresh, green roots were collected, cut into lengths appropriate for the testing machine (20 to 30 cm), and kept moist. The bark was shaved from the ends of the root to reduce slippage of the roots during testing. Electrician's cable pullers were used to hold the root. The bias weave of the cable puller allowed for tight holding with little damage to the root. The root was placed between two rods: one was stationary and the other displaced at a rate determined by the operator. The time for an individual test varied from 15 seconds to about 1 minute. Displacement was increased and the load was monitored until the root broke in tension.

The average tensile strengths of sugar maple root and of white ash root are 2.85×10^4 kilopascals (correlation coefficient $r^2 = 0.90$) and 2.22×10^4 kilopascals ($r^2 = 0.83$), respectively; this difference in tensile strength is not statistically significant. The results of the laboratory testing of root strength in association with the field measurements of root pull-out resistance illustrate the following:

1. Although the graphs of pull-out resistance versus displacement for the tested roots vary widely, they can be divided into three general categories (fig. 7). In all three categories, force initially rises abruptly with little or no displacement, but this initial peak is followed by a gradual reduction of force in category I roots, by continued high force leading up to a final abrupt fall-off in category II roots, and by an interim reduction of force and then a second abrupt peak in category III roots.

The three basic force-displacement categories are associated with different root morphologies. Category I roots are generally long (0.8–1.5 m), straight segments with few to moderate numbers of branches. They have one or two large, truncated termini aligned in the same direction in which the root was pulled. Category II roots are short (0.1–0.7 m), highly branched segments that have large numbers of thin truncated termini. Most category III roots are forked into two major branches, which diverge at an angle of 45° or more in most cases. A sketch of each root is shown with a graph of force versus displacement in figure 7.

2. The measured tensile breaking force (mtbf) of a root being pulled from soil increases with root diameter for both sugar maple and white ash (fig. 8). The tensile breaking force, or pull-out resistance is the *final* peak in force which causes failure; all forces applied subsequently are smaller in magnitude. It may or may not be the greatest force which was applied to the root in the pull-out test. The "m" in the abbreviation "mtbf" denotes that the breaking force was measured in field tests, rather than predicted ("p") from laboratory tests of root strength.

3. The laboratory-measured tensile force required to break a root of a specified diameter (ptbf) is greater than the field-measured pull-out resistance for a root of a similar diameter (mtbf). The difference between pull-out resistance (mtbf) and predicted tensile breaking force (ptbf) is shown by the best-fit lines in figure 9. The pull-out test shows that root failure occurs at various distances away from the applied force, as demonstrated by the different lengths of broken roots of similar diameters. Thus, the root fails as an anchor; it displaces under tension and then breaks within the soil at a distance from the applied axial force.

4. The load rate does not affect the measured force needed to break a root. This independence was demonstrated in a stepwise multiple regression test of variables possibly affecting root strength (Riestenberg, 1987). This relationship differs from that described by Fraser (1962) in his study of the pull-out resistance of the roots of softwoods, in which he showed that the measured force increased with loading rate.

5. The branches of a root break sequentially as the root displaces within the soil. However, the sequence of failure of the branches within the soil cannot be determined from the field data. The force to break all truncated termini at once (srs) was estimated by measuring the diameters of all the broken ends on roots extracted by the pull-out tests, calculating the force needed to make each of these breaks based on

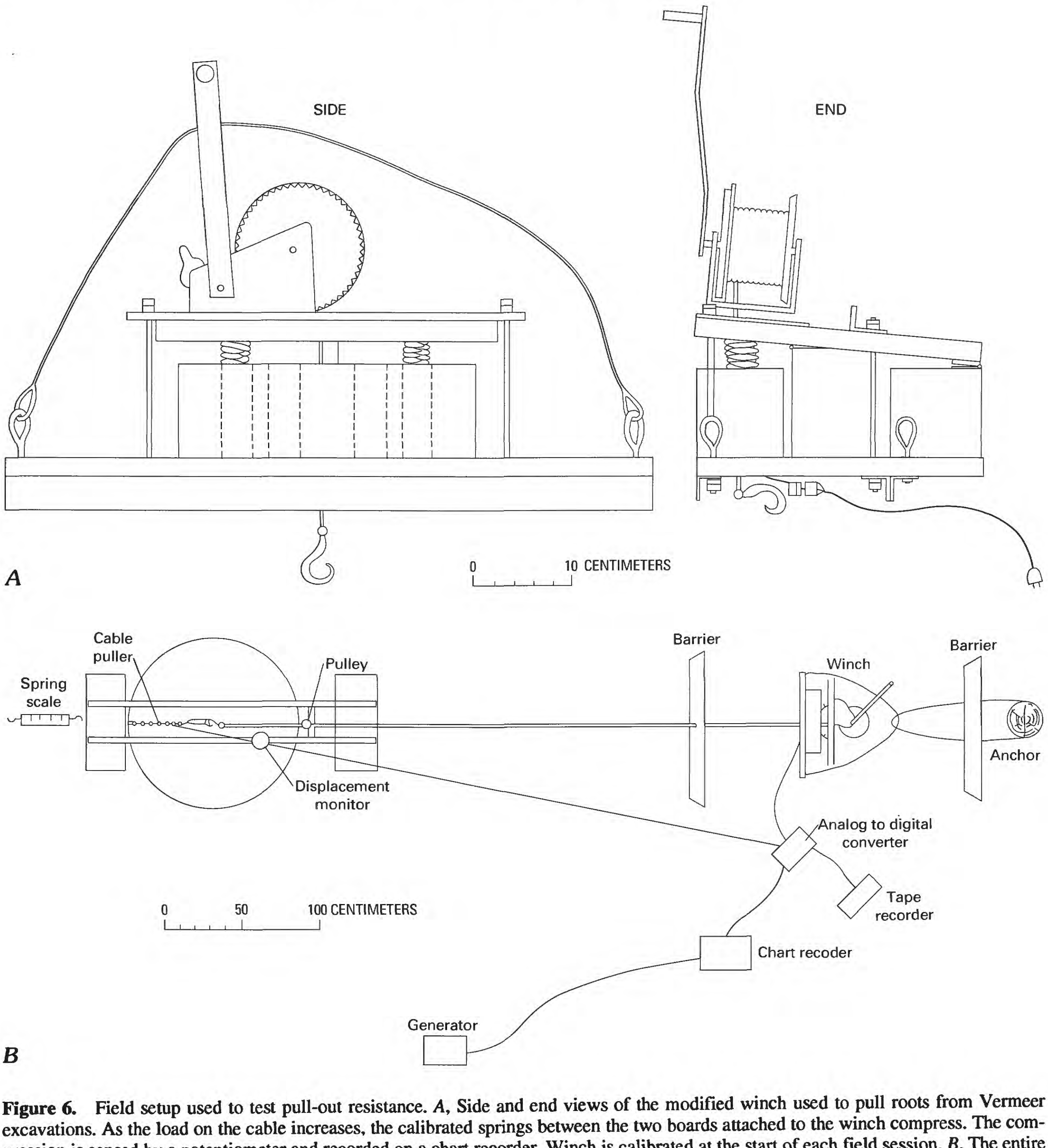


Figure 6. Field setup used to test pull-out resistance. *A*, Side and end views of the modified winch used to pull roots from Vermeer excavations. As the load on the cable increases, the calibrated springs between the two boards attached to the winch compress. The compression is sensed by a potentiometer and recorded on a chart recorder. Winch is calibrated at the start of each field session. *B*, The entire testing array. Both load and displacement are measured for each root and recorded on a chart recorder powered by a portable generator.

laboratory tests of root strength, and then summing all the forces thus calculated. In all cases the resulting total force was greater than that predicted by laboratory tests to break a root of the diameter exposed at the excavation face (ptbf) (fig. 9), which in turn is greater than the field-measured pull-out resistance (mtbf). This difference in breaking forces develops because the sum of the cross-sectional areas of the termini of broken branches is greater than the cross-sectional area of the root trunk exposed at the soil face, and the breaking strength of the roots within the species is essentially a function of cross-sectional area for the range of root diameters tested.

6. There is no preferred plane in the colluvial soil within which roots tend to break, despite differences in soil texture and gradients in soil moisture.

SPATIAL DISTRIBUTION OF ROOTS IN COLLUVIUM

In order to estimate the areal spacing, sizes, and types of root anchors that would most likely project through a shear surface at some discrete depth within the soil, I studied the root systems of sugar maple and white ash, tree species that dominate the Cincinnati hillslopes. This study was limited to trees ranging from 6 to 16 cm in diameter, because trees of this size dominate the Rapid Run landslide and because trees of this size may be removed by a Vermeer spade. Roots were excavated and described at the Delhi and Spring Grove sites. Various excavation and sampling methods were combined for the study. Three trees were hand-excavated, one at the Delhi site and two at the Spring Grove site. The root morphologies were compared with those of 11 trees at Spring Grove that were excavated by a Vermeer spade.

MORPHOLOGY AND DISTRIBUTION OF THE ROOTS OF SUGAR MAPLE

Figure 10 shows the root system of the understory-sized sugar maple chosen for excavation at the Delhi site. The maple was growing 2–3 m from canopy trees within an area in which the soil had been thinned to 0.5 m by landsliding. The tree, designated sugar maple 1, had a height of 6 m, diameter at breast height (dbh) of 6 cm, and a crown width of 4 m. The roots of the maple were excavated with a trowel and a hand rake. The diameter, azimuth, and plunge of the main roots and branch roots were measured between branches at 10 cm from branching points.

The taproot of the excavated maple vertically penetrates the upper 20 cm of soil, then branches, narrows, and bends to align itself subparallel with the ground surface (fig. 10). The large lateral roots originate in swelled areas on the tap root and radiate from the base of the tree. The swelled areas project laterally about 4–5 cm or more from the tap, then terminate where the branching occurs (fig. 10). Individual lateral roots taper gradually and branch at random; the branches grow at an angle of about 45° from the root and are one-third to one-half the diameter of the root. The roots taper, at first markedly, then more gently, until they reach about crown width (in this case, about 2 m from the trunk), where they terminate in highly branched fans of tiny rootlets. These terminal rootlets are nonwoody and fragile. In addition, many sinker roots, about 1 cm or less in diameter, originate from the large lateral roots and from branches off the laterals.

Figure 11 demonstrates the high concentration of the roots of the excavated maple near the ground surface and the abrupt decline in concentration with depth. The high concentration of roots in the top 0.6 m of soil is consistent with root distributions described in hardwood forests studied by Scully (1942), Kochenderfer (1973), and Stout (1956). A maple excavated at the Spring Grove site (sugar maple 2, fig. 12) has a similar shallow rooting habit, even though it grew in deeper colluvium than sugar maple 1 and was not obstructed by bedrock. This understory-sized tree grew in a heavily wooded area of the Spring Grove woodlot dominated by sugar maple and white ash. At the excavation site, the land slopes at 8° and the soil averages 1.5 m in thickness. The soil type at each site is the same, and both trees grow within a mature hardwood forest. The only known differences between the sites are the ground slope and aspect and the depth to bedrock.

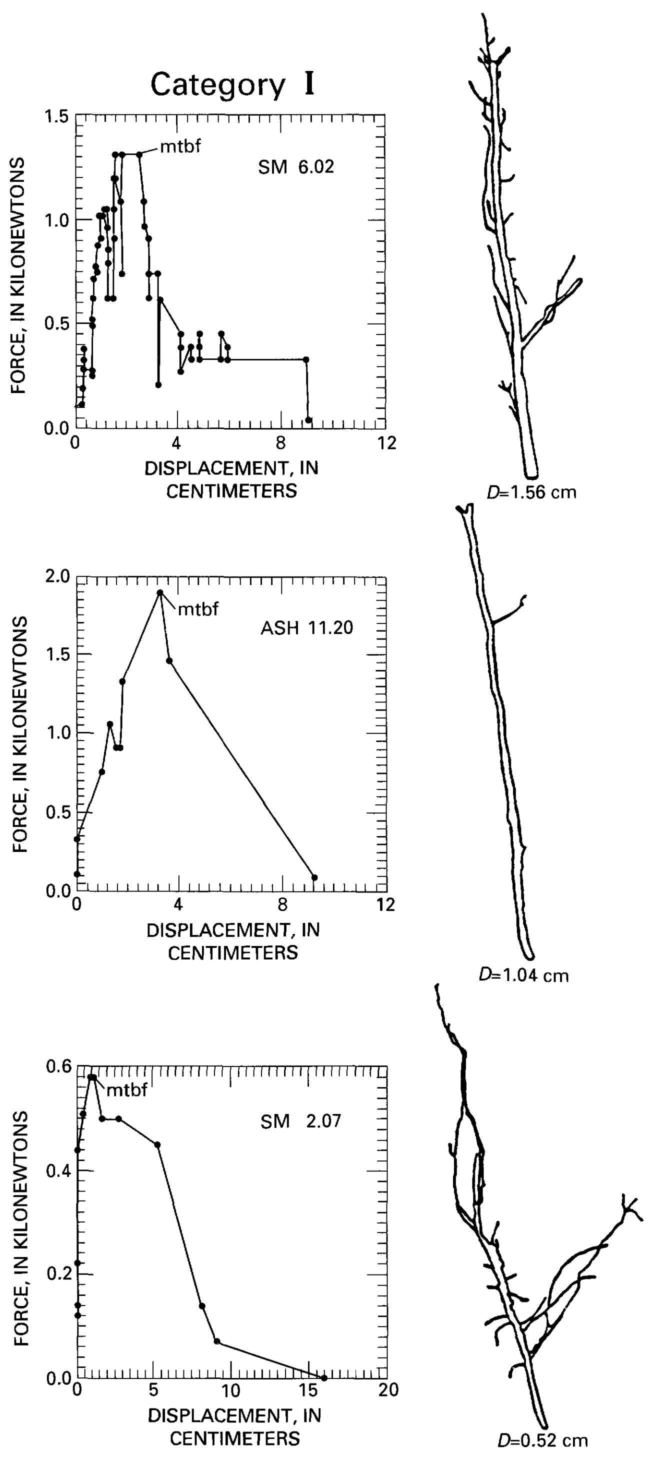
The root system of the sugar maple at Spring Grove (fig. 12) has the same general form as that of sugar maple 1 at the Delhi site (fig. 10). The taproot abruptly reorients from vertical to parallel with the ground surface. Swelled projections from the taproot branch near the trunk into lateral roots which radiate from the center of the tree. The laterals branch at high angles to the source root. The abundant branching and rapid tapering of the roots gives them a spindly appearance. Upon tapering to about 0.5 cm in diameter, the roots project as more gradually tapering tubes for as much as 2 m. These narrow tubes terminate in fans at about crown width (3–4 m from the center of the tree).

Root asymmetry has been correlated with surface gradient (Parizek and Woodruff, 1957), but for both sugar maples 1 and 2, the radial distribution of roots seems unaffected by slope, at least within 50 cm of the trunk (figs. 10 and 12).

Roots of several sugar maples ranging from 8 to 15 cm dbh were observed at excavations made by a truck-mounted spade to determine whether the distributions described for the two hand-excavated maples are representative of small maples growing in colluvium in Cincinnati (Riestenberg, 1987). The spade-excavated sugar maples show essentially the same rooting habit near the base of the tree that was seen in the hand-excavated sugar maples; the numbers and cross-sectional area of roots are highest near the ground surface, and diminish in number with depth. The roots displayed the same spindly form as those of the excavated trees, with the laterals tapering highly as they branched, and the taproot reorienting from vertical to become parallel with the slope near the base of the tree.

MORPHOLOGY AND DISTRIBUTION OF THE ROOTS OF WHITE ASH

A white ash, 8.8 cm in diameter, was selected for hand excavation at the Spring Grove site. It grew 5 m from the



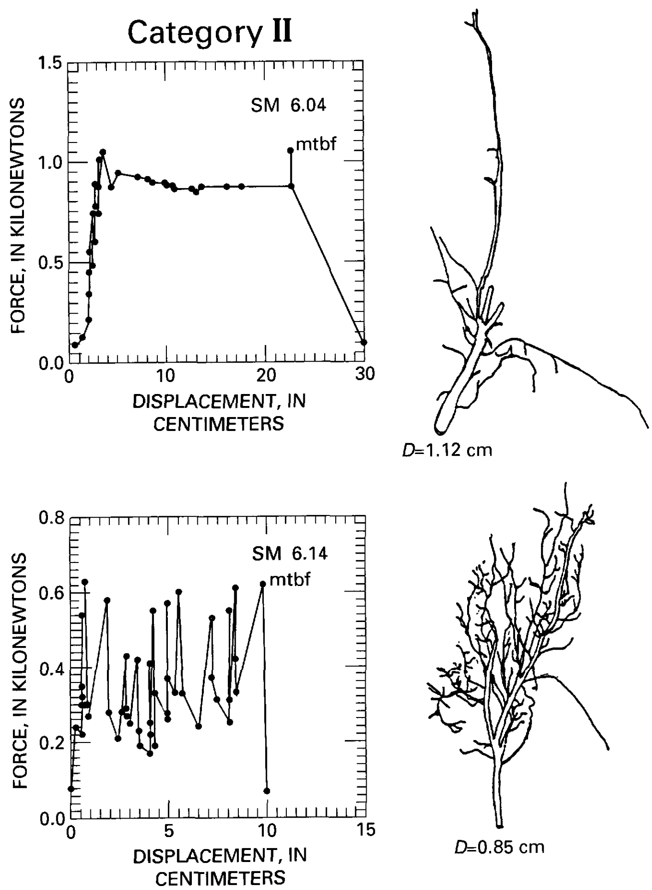
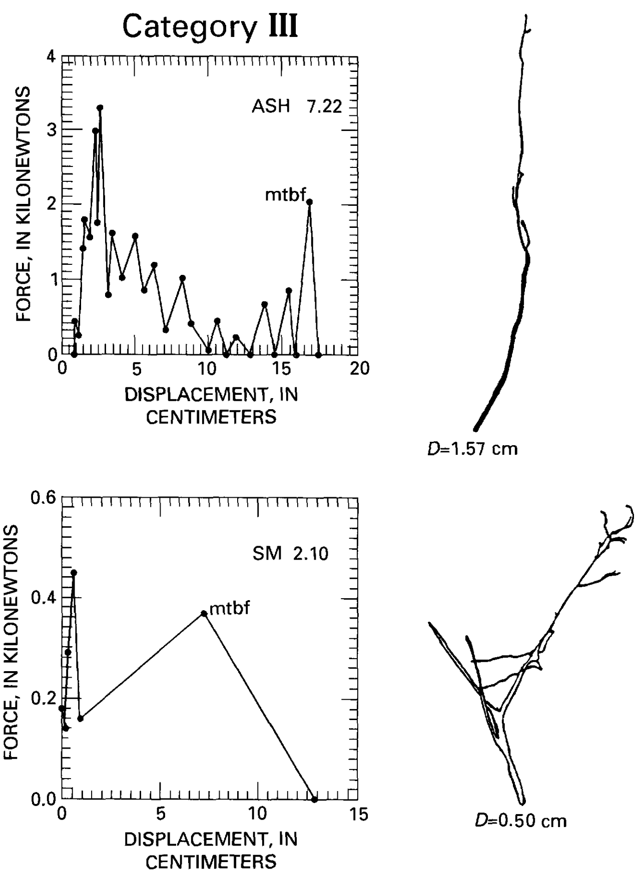


Figure 7 (above and facing column and facing page). Three general categories of roots and their force-displacement relationships. As any root of these three categories is pulled out, force initially rises abruptly with little or no displacement, but this initial peak is followed by gradual reduction of force in category I roots, by continued high force leading up to a final abrupt fall-off in category II roots, and by an interim reduction of force and then a second abrupt peak in category III roots. Category I roots are generally long and poorly branched, category II roots are short and highly branched, and most category III roots fork in two major branches. In these figures, SM stands for sugar maple, *D* is the diameter of the illustrated root segment at its proximal end, and mtbf, the measured tensile breaking force, is the final peak in force that causes failure; all forces applied subsequently are smaller.

sugar maple that was excavated from the woodlot. All roots of the excavated white ash larger than 0.075 cm are woody. The branches extend to a depth of 1 m below the ground surface and then reorient horizontally. The taproots are intermittently branched; the branches are at high angles to the taproot and are generally less than 1 cm in diameter.

The taproot has the form of a cone, rather than the cylindrical shape of the laterals. Its branches also taper strongly as they project nearly vertically into the colluvium. The lateral roots radiate from the taproot and disperse about the trunk. In some places individual laterals originate directly from the taproot whereas, in other spots, groups of two or more fuse at their heads to form swellings on the side of the taproot. As the laterals radiate from the tree, they generally project in the same direction in which they started (fig. 13). The roots are circular in cross section and taper gradually, so they appear almost cylindrical in shape, in contrast to the highly tapering and branched roots of the maple. This difference in taper gives the two species their characteristic shapes: the sugar maple appears to be spindly, and the ash appears to be massive.



Some lateral roots of ash terminate as fans of tiny rootlets; others terminate abruptly (fig. 13). The termini of the blunt lateral roots are sealed with a waxy covering and reflect root mortality or cessation of growth (Kramer and Kozlowski, 1979). (Blunt termination is observed infrequently in sugar maple).

Unlike the shallow roots of the sugar maple, the lateral roots of the ash may plunge steeply. One lateral of the ash projects at an angle 55° from horizontal, and continues to a depth of 1 m below the ground surface. It has 34 branches along its 1.8-m length beyond the point at which it reorients horizontally. It has a higher rate of taper than the horizontal laterals.

The spade-excavated roots of five white ash trees at the Spring Grove site are similar in form to the hand-excavated ash roots. Roots exposed by both hand excavation and truck-mounted spade are distributed in two distinct directions within the soil: a set of laterals extends nearly horizontally, and a very large, branched taproot projects vertically. The laterals are large, have few branches, and taper gradually. The dominant vertical taproot is typical of ash trees (Riestenberg, 1987).

COMPARATIVE ANALYSES OF ROOTS OF SUGAR MAPLE AND WHITE ASH

The observations of the roots of sugar maple and white ash demonstrate that rooting habits differ greatly between the two species and that, in general, the overall root configurations for both species are predictable. Figure 14 shows the roots of sugar maple and white ash trees that were excavated by a Vermeer spade. The trees have the same diameter trunk, but the roots are quite different in form. The root balls shown in figure 14 represent 2 of 11 trees that were removed from the Spring Grove site.

The differing root distributions of sugar maple and white ash are illustrated by stereonets showing contours of root area as a function of orientation at a distance of 30 cm from the bases of the three fully excavated trees (fig. 15). The sugar maple roots are concentrated at low angles from the base of the tree, whereas the white ash roots are concentrated in two orientations: one nearly horizontal and the other vertical.

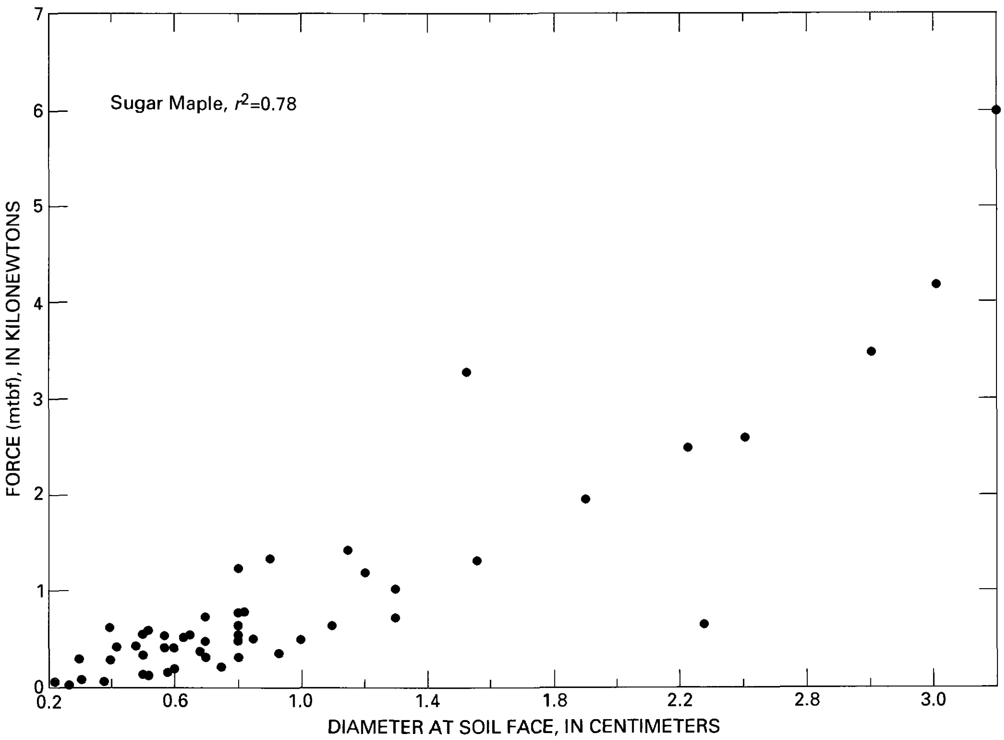
Root area and depth are compared for the two species in figure 16. The cross-sectional area of roots penetrating various depths for all three excavated trees is highest near the ground surface, and decreases rapidly with depth. The root areas of the sugar maples approach zero at a depth of 60 cm, but the tap root of the ash projects to a depth of 110 cm.

Rose diagrams of orientations of the lateral roots of the fully excavated trees and those sampled by the Vermeer spade excavations show similarities between the two species (fig. 17). The measurements are made at a distance of 30 cm from the base of the tree trunk. The laterals tend to be spaced nonpreferentially about the trunk, despite differences in slope. No preferred orientation of roots was observed on the more steeply sloping Delhi site.

Roots of trees larger than the fully excavated trees show distributional trends similar to those described above. Observations of trench faces cut near trees of varying sizes showed that roots are most numerous in shallow soil to a depth of 6–8 cm and then decrease sharply in abundance with depth. Kramer and Kozlowski (1979) point out that rooting depth shows no correlation with the above-ground size of the plant. Few roots larger than 1 cm in diameter extend through soil 2 m below the ground surface (fig. 18).

STABILITY ANALYSIS OF A HILLSLOPE UNDERLAIN BY COLLUVIUM ANCHORED BY SUGAR MAPLE AND WHITE ASH ROOTS

The data collected on pull-out resistance and distribution and morphology of roots can be incorporated into a stability analysis to determine how effective the roots of sugar maple and white ash are in stabilizing hillslopes. The



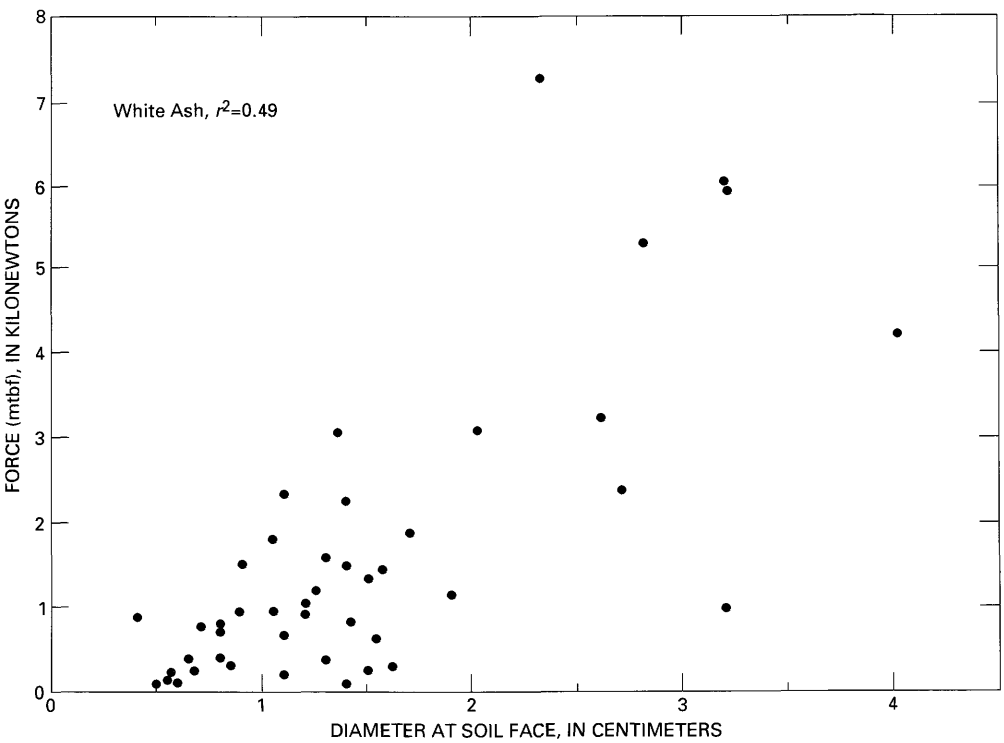
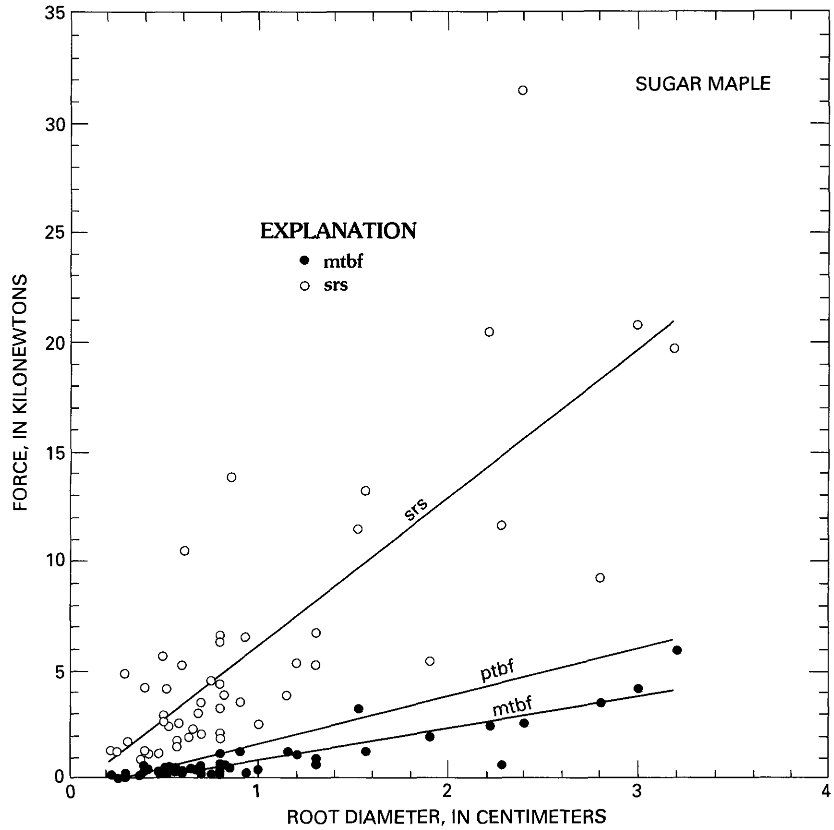


Figure 8. The tensile breaking force (mtbf) measured for two roots during extraction. The factor that best predicts the pull-out resistance of a root is its diameter. A secondary factor affecting pull-out resistance is the length of the root. Correlation coefficient for each root type shown as r^2.



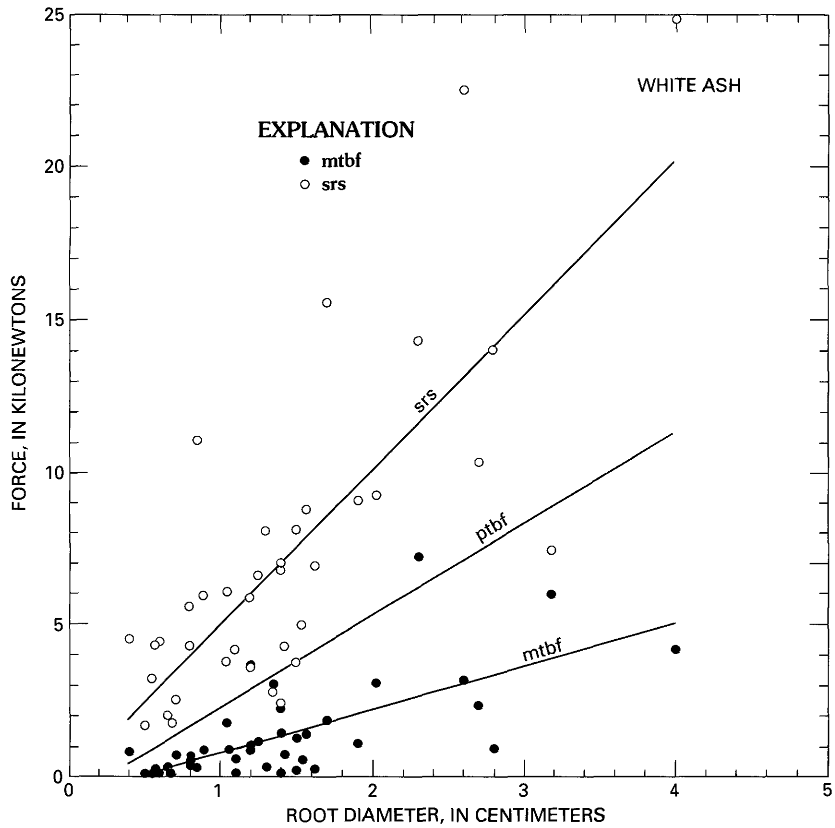


Figure 9. Root diameter versus predicted tensile breaking force (ptbf), predicted force to break all termini at once (srs), and measured tensile breaking force (mtbf). (See figures 7 and 8.) The force predicted to break all termini within the colluvium at once (srs) is greater than the force predicted to break a root of the diameter exposed at the trench face (ptbf), which in turn is greater than the measured tensile breaking force (mtbf) applied to the root. These observations invalidate the assumptions used in the model for the Rapid Run landslide (Riestenberg and Sovonick-Dunford, 1983)—that is, that all roots break at once and that the tensile breaking force is determined by the diameter of the root that projects through the shear surface in the soil.

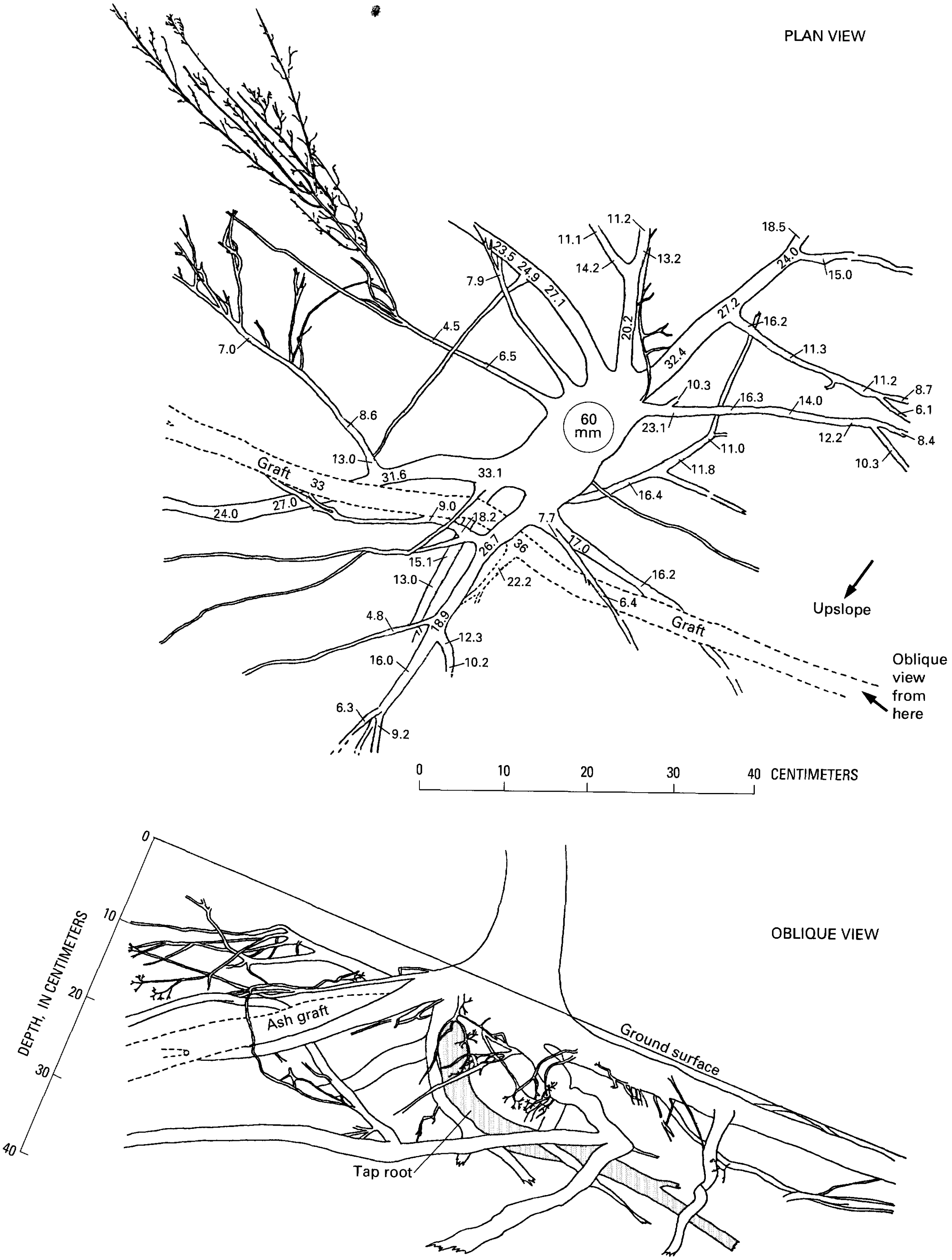


Figure 10. Plan and cross-sectional views of the excavated roots of sugar maple 1 from the Delhi site. Root diameters, in millimeters, are shown in the plan view. The roots are numerous, are highly branched, and are concentrated within the uppermost soil horizons. The roots taper markedly with distance from the trunk, a characteristic associated with frequency of branching.

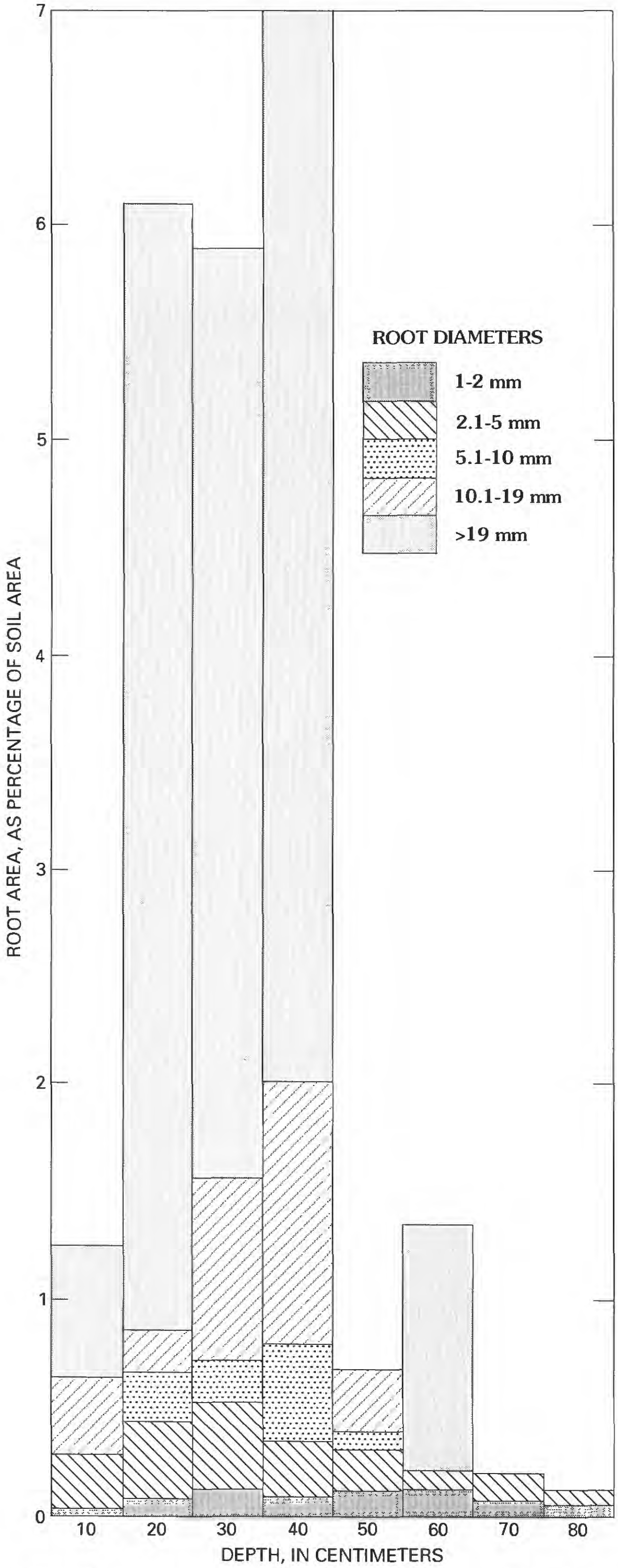


Figure 11. The density of roots as a function of soil depth. The cross-sectional area of roots per area of soil exposed at a trench face decreases markedly with depth (Riestenberg and Sovonick-Dunford, 1983).

stability analysis uses data from the Delhi and Spring Grove sites along with measurements of the residual strength of the colluvium made by Fleming and Johnson (1994). For an anchored soil block lying at equilibrium on an inclined surface, such as the bedrock-soil interface, factors that resist failure of the block are the strength of the soil, S_s, and the strength of the anchors; factors that drive failure are the unit weight of the soil mass, γ, and the slope angle, β Soil strength is defined by the Terzaghi-Coulomb equation as:

$$S_s = c + \sigma' \tan \phi \qquad (1)$$

where

c = cohesion for effective stress

σ' = effective normal stress, and

ϕ = soil internal friction angle for effective stress

For a block of soil of volume v resting on an inclined plane (hillslope), assuming the water table is at the ground surface and flow is parallel to the slope, the force resisting basal shearing is:

$$AS_s = v(\gamma_t - \gamma_w) \cos \beta \tan \phi + cA \qquad (2)$$

where

$v = AT$, volume of soil block

A = area of base of block

β = slope angle

T = thickness of soil

γ_t = unit weight of the saturated soil, and

γ_w = unit weight of water

If an anchor projects through the block into the underlying material at an angle, α, from normal, the block resists shear by:

$$AS_a = F \cos \alpha \tan \phi + F \sin \alpha \qquad (3)$$

where

F = tensile force on anchor (assumed positive), and

AS_a = resistance of anchored block to shear.

The forces that resist failure, F_r, equal AS_a plus AS_s, the block's resistance to shear. The forces driving failure of the anchored block are:

$$F_d = v(\gamma_t) \sin \beta \qquad (4)$$

Thus, the factor of safety against sliding, FS, is equal to:

$$FS = \frac{F_r}{F_d} = \frac{\left(1 - \frac{\gamma_w}{\gamma_t}\cos\beta + \frac{F}{\gamma_t v}\cos\alpha\right)\tan\phi + \frac{F}{\gamma_t v}\sin\alpha + \left(\frac{A}{v}\right)\frac{c}{\gamma_t}}{\sin\beta} \qquad (5)$$

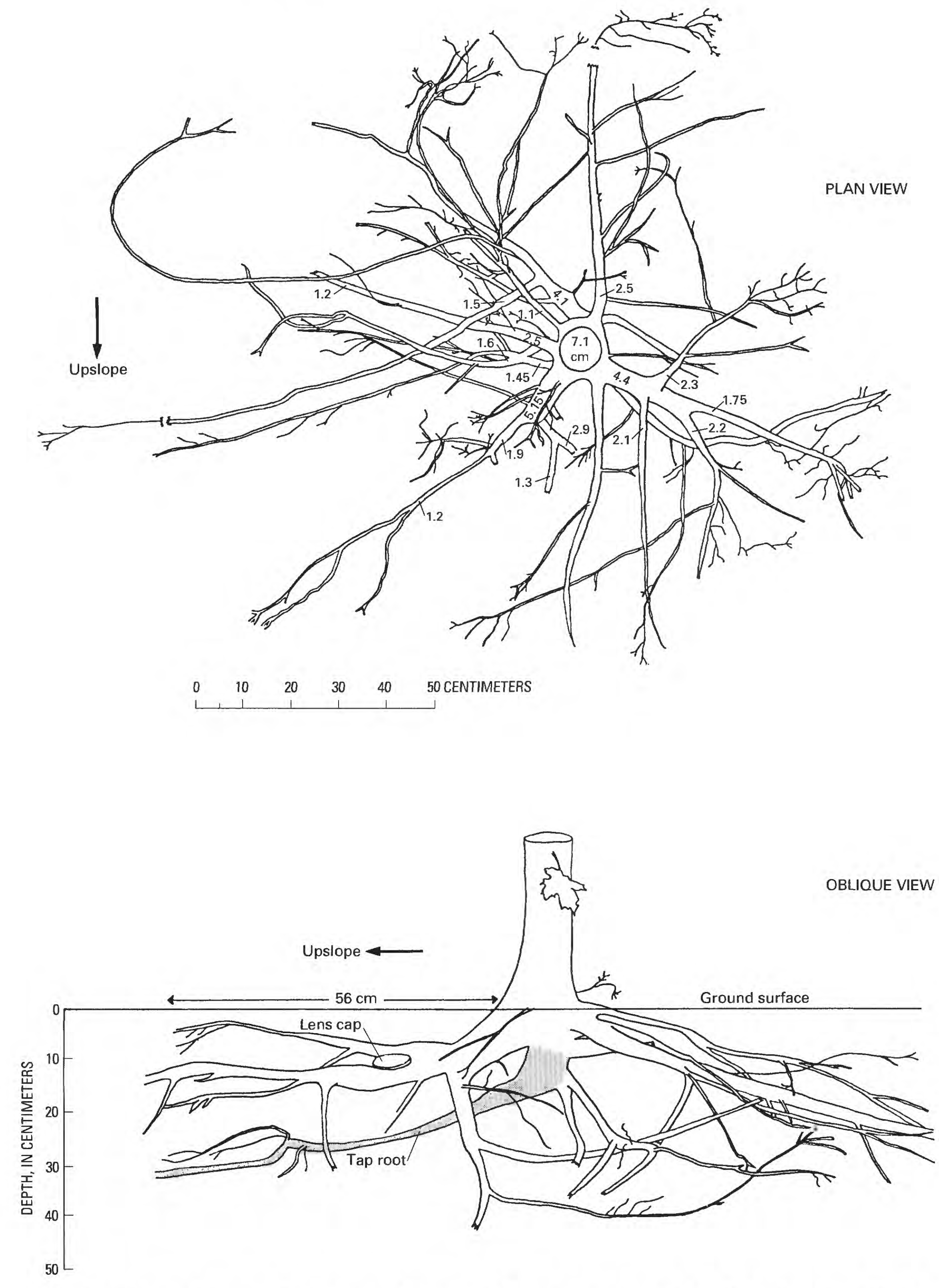


Figure 12. Plan and cross-sectional views of the excavated roots of sugar maple 2 at the Spring Grove site. Root diameters, in centimeters, are shown in the plan view. The general distribution and morphology of the roots are similar to those of the maple excavated at the Delhi site. This tree, however, grows on gently sloping terrain underlain by deep colluvium, whereas the one at the Delhi site grew on a steep hillslope underlain by a thin mantle of colluvium.

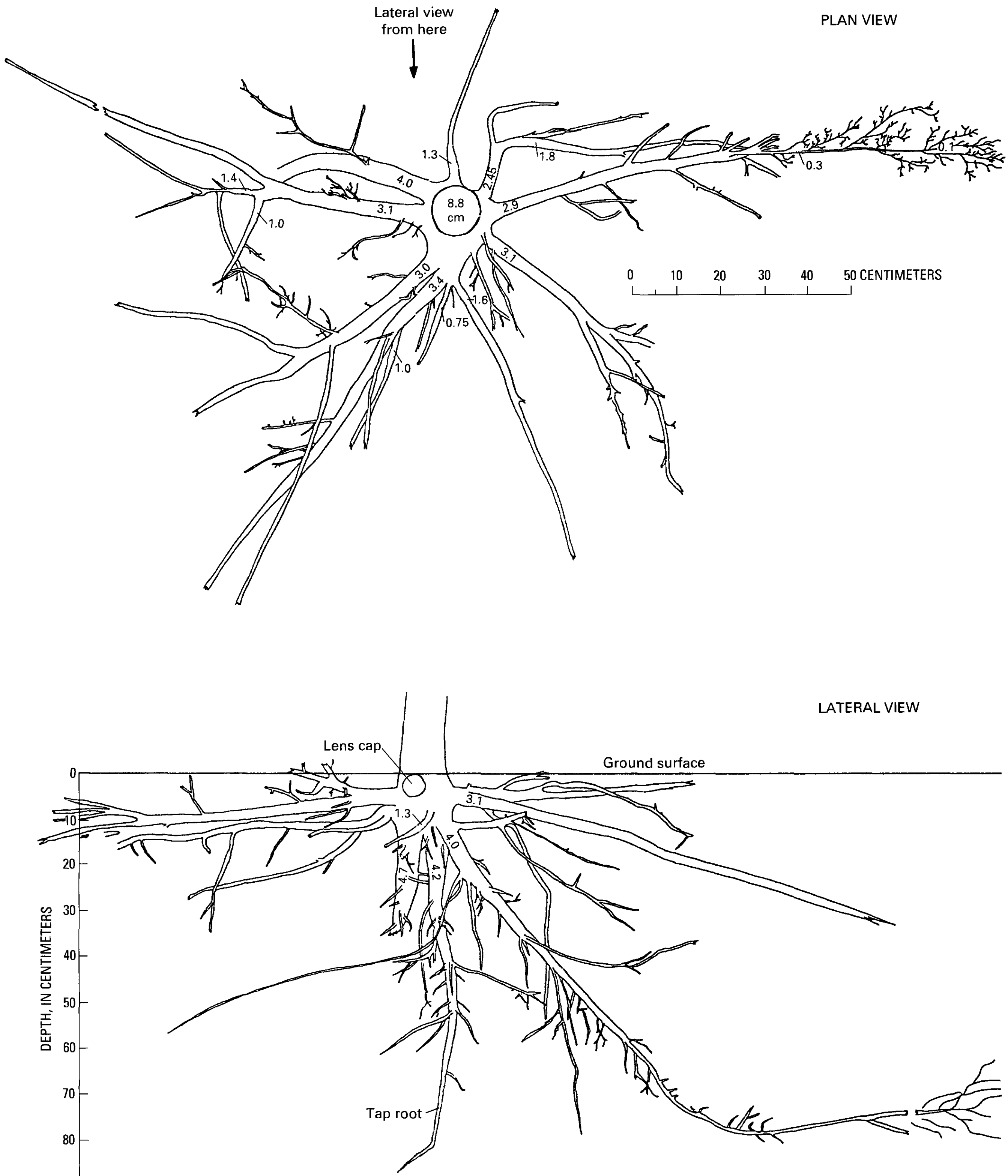


Figure 13. Plan and cross-sectional views of the excavated roots of a white ash at the Spring Grove site. Root diameters are shown in centimeters. The roots of the ash tree have two contrasting orientations: one set of roots is nearly parallel with the ground surface, and another set is at high angles to the ground surface. The tree is similar in girth to the excavated sugar maple, which grew next to it, but the roots of the ash extend deeper into the colluvium.

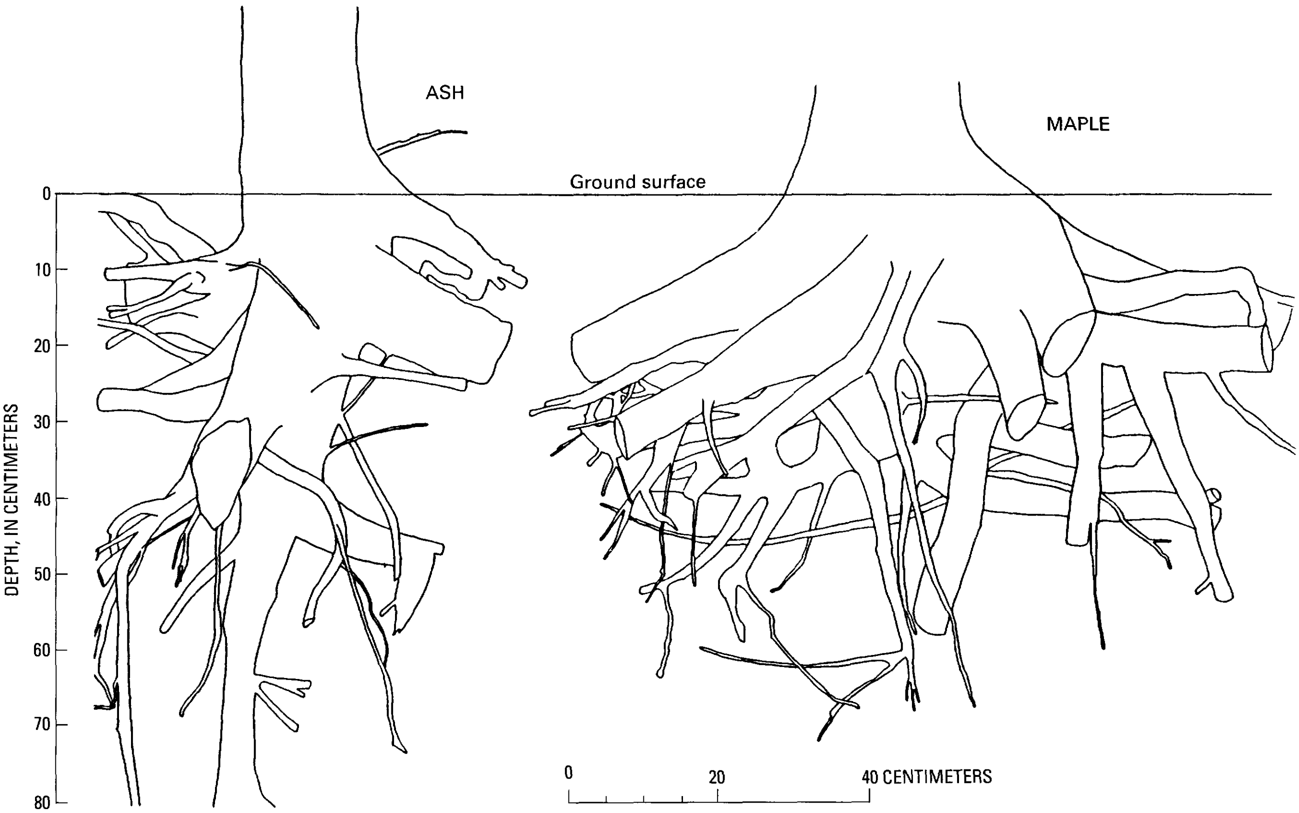


Figure 14. Lateral view of sugar maple and white ash roots removed from the colluvium by the Vermeer spade. The orientations and characteristics of the roots near the trunk are similar to those described for the hand-excavated roots. The ash, in contrast to the highly branched maple, has a root system that is dominated by a large tap root. (Illustration by Ted Riestenberg).

As the anchored soil displaces, tensile forces, F, are mobilized in the roots that anchor the mass to a stable substrate below the colluvium. The tensile forces that develop in the roots are a function of the root type and size, and the magnitude of displacement of the anchored soil block. For example, a category I root (fig. 7) will develop peak resistance to failure at about 2 cm of displacement, at which point the root will contribute its greatest force resisting failure.

The computer program DEPTH (written by Roger Stuebing, University of Cincinnati) uses measurements from hand-excavated trees of the azimuth, plunge, and starting and ending diameters of each unbranched segment of root to determine the numbers and diameters of roots that penetrate planes parallel to the ground surface at various depths beneath a tree (Riestenberg, 1987). The computer program lists the sizes and orientations of the roots projecting through soil planes at depths selected for the stability analyses.

The force-displacement relationships of 19 roots, each belonging to one of the three root categories (fig. 7), are used in developing stability analyses of wooded hillslopes. The roots chosen are of differing sizes and were growing at various orientations within the soil before they were pulled out.

A root is selected from the 19 type roots to represent each root segment enumerated by the program for the stability analysis of soil of a thickness corresponding to the chosen depth or soil plane. The root is selected on the basis of its size, orientation, and type. For instance, for a small root projecting through a shallow plane, a type root is selected from the set of category II roots, because those roots are highly branched as shallow roots observed in the excavations. A steeply plunging root is represented by a type root from either category I or category III, depending on the depth of the plane. A root that projects through a deep plane is poorly branched, like roots of category I, and a root projecting through a more shallow plane is branched like a category III root.

Figure 19 and table 1 illustrate the results of a stability analysis for a block of colluvium inclined at 30°. The block width and length are each 1 m; its thickness is 0.43 m. The soil properties used in the analysis are the residual strength values measured for remolded colluvium (Fleming and Johnson, 1994). Constants used in this analysis and those that follow are listed in table 1.

The stability analysis uses several roots, each of which has a different relationship between force and displacement. The root anchors are assumed to be aligned perpendicular to the shear surface, so α, the root angle, is zero. This simplifying assumption is based partly on observations of the orientations of small roots that cross shear surfaces, and partly on the limitations set by the field testing of pull-out

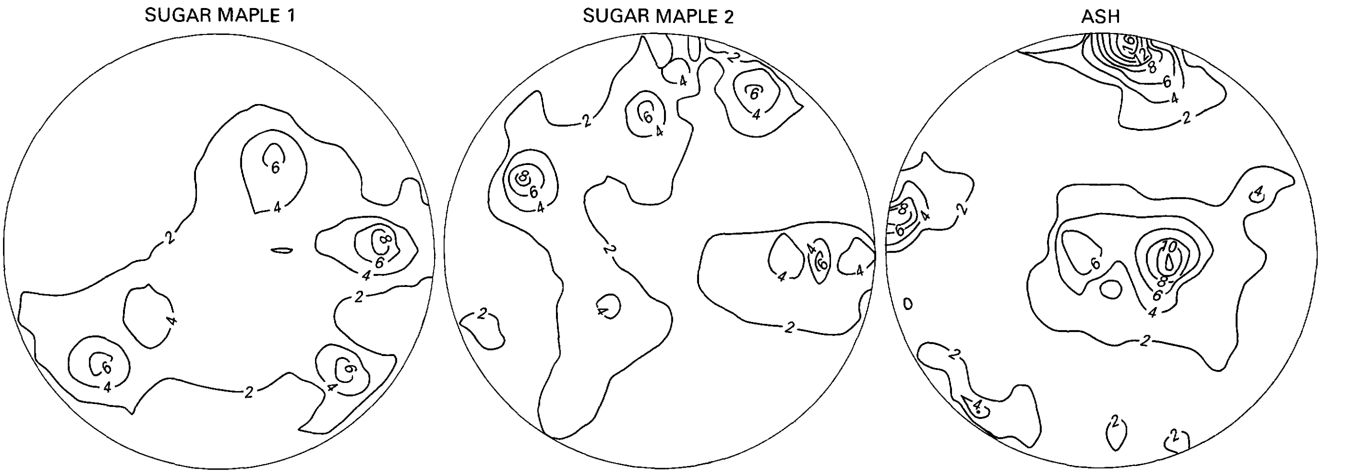


Figure 15. Stereonets of cross-sectional area of roots cutting the surface of a lower hemisphere at a radius of 30 cm from the base of the trunk. The contour interval is 2 cm^2. The two species show contrasting root distribution. The sugar maple roots are most concentrated at low angles from the horizontal, and the white ash roots are concentrated at low and high angles from the horizontal. The sugar maple is shallow rooted; the white ash is deeply rooted due to its dominant, vertically oriented tap root.

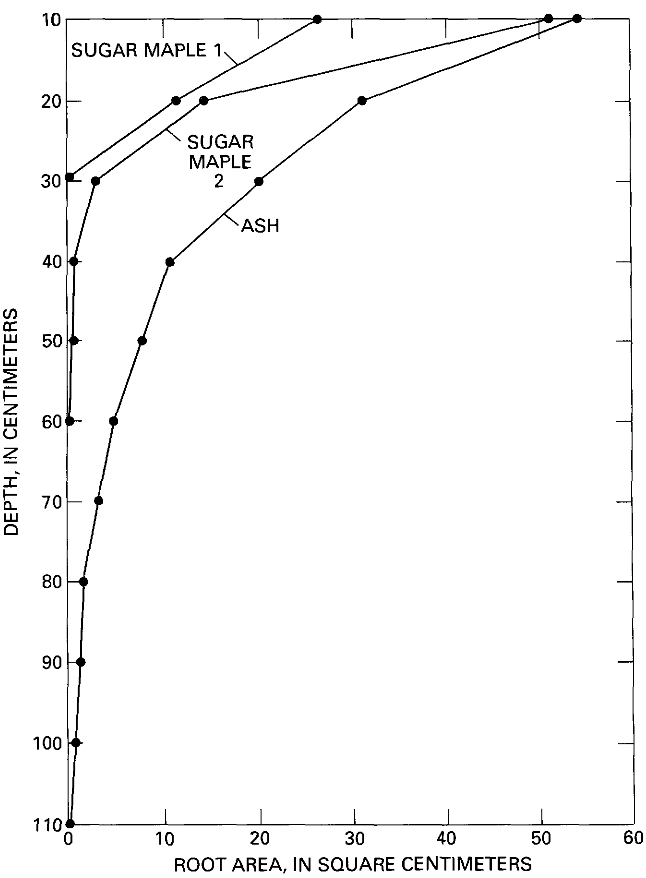


Figure 16. The cross-sectional area of roots of the hand-excavated trees as a function of depth. The roots of both species are concentrated in number and size in shallow colluvium, and decrease in numbers and cross-sectional area with depth. The maple roots extend to 0.6 m and the white ash roots to 1.1 m below the ground surface. The plot is drawn using orientations and dimensions of the roots of the fully excavated trees.

resistance. The size of the Vermeer excavations used in field testing limited the pulling direction to nearly perpendicular to the excavation face, collinear with the long axis of the exposed roots.

The number and sizes of roots that penetrate the shear surface at 0.43 m depth were calculated for the trees that were hand excavated at the Spring Grove site (fig. 19) (Riestenberg, 1987). The depth of 0.43 m chosen for the analysis approaches the critical thickness of the block without roots—that is, the thickness at which the factor of safety (resisting force/driving force) equals unity. This thickness is 0.42 m. Figure 19 shows that for colluvium anchored by either maple or ash, the factor of safety exceeds 1 at the first hint of movement. The subsequent increase with further displacement is much greater for colluvium anchored by ash than for that anchored by maple. This difference in anchoring is due to the difference in root mass at depth between the two species.

CRITICAL SPACING OF ASH TREES ON A HILLSLOPE

The density of roots within soil affects the soil's resistance to shear, and, because roots are most concentrated near the base of the tree from which they originate, it follows that close spacing of trees will strengthen soil. A stability analysis of an inclined colluvial soil block supporting an ash tree shows that the factor of safety decreases with increasing spacing of trees (fig. 20). The analysis uses the dimensions of the excavated ash from Spring Grove and a soil block 0.43 m thick. The area of the block and, hence, the shear-surface area vary. The initial area of the block's shear surface is 1 m^2, which is equivalent to 1-m spacing

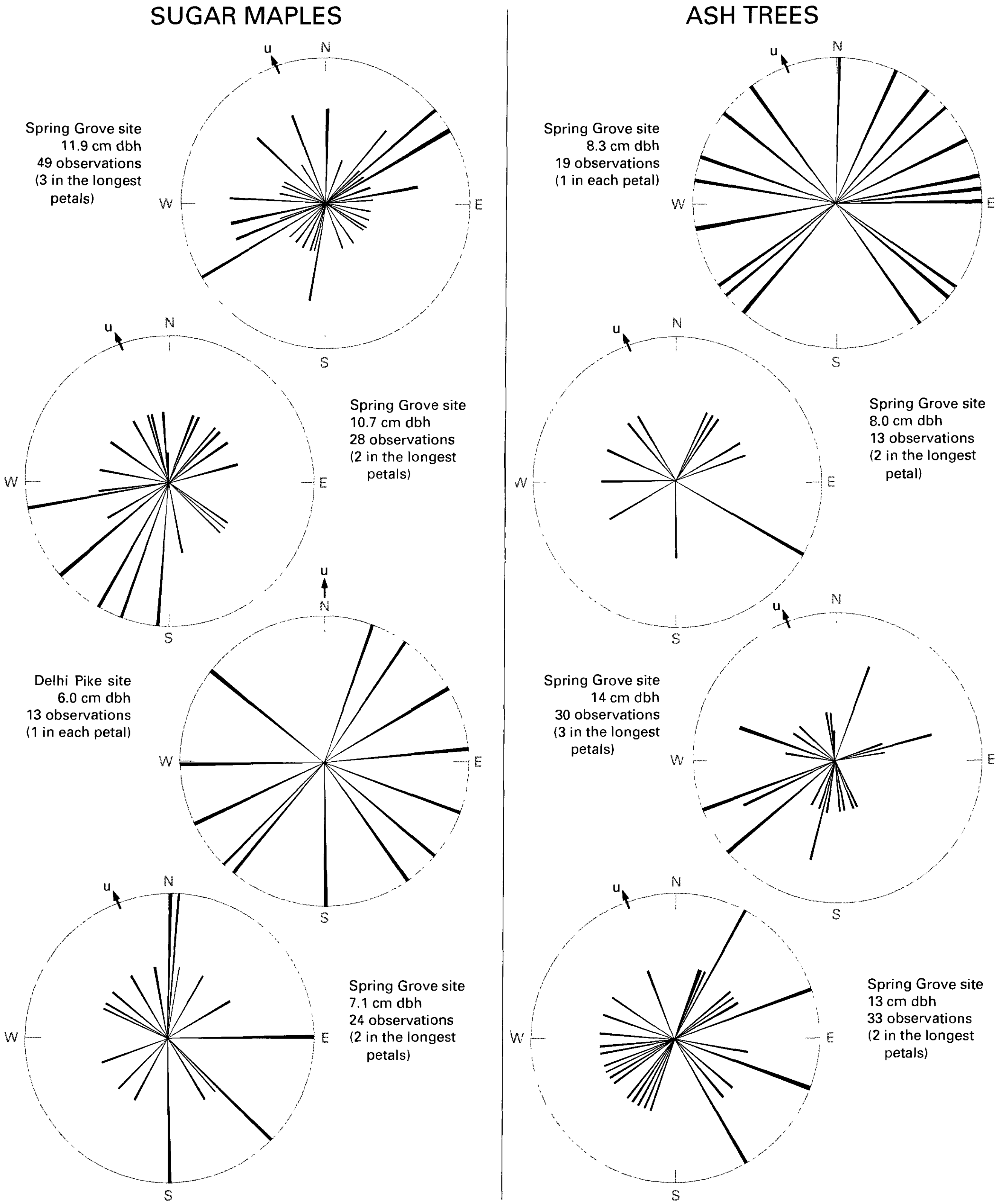


Figure 17. Azimuths of lateral roots of sugar maple and white ash trees from the Delhi and Spring Grove sites. In both species, root distribution appears random and unaffected by slope; none of the specimens showed any strong directional trend. U marks upslope side of each diagram; dbh is diameter at breast height.

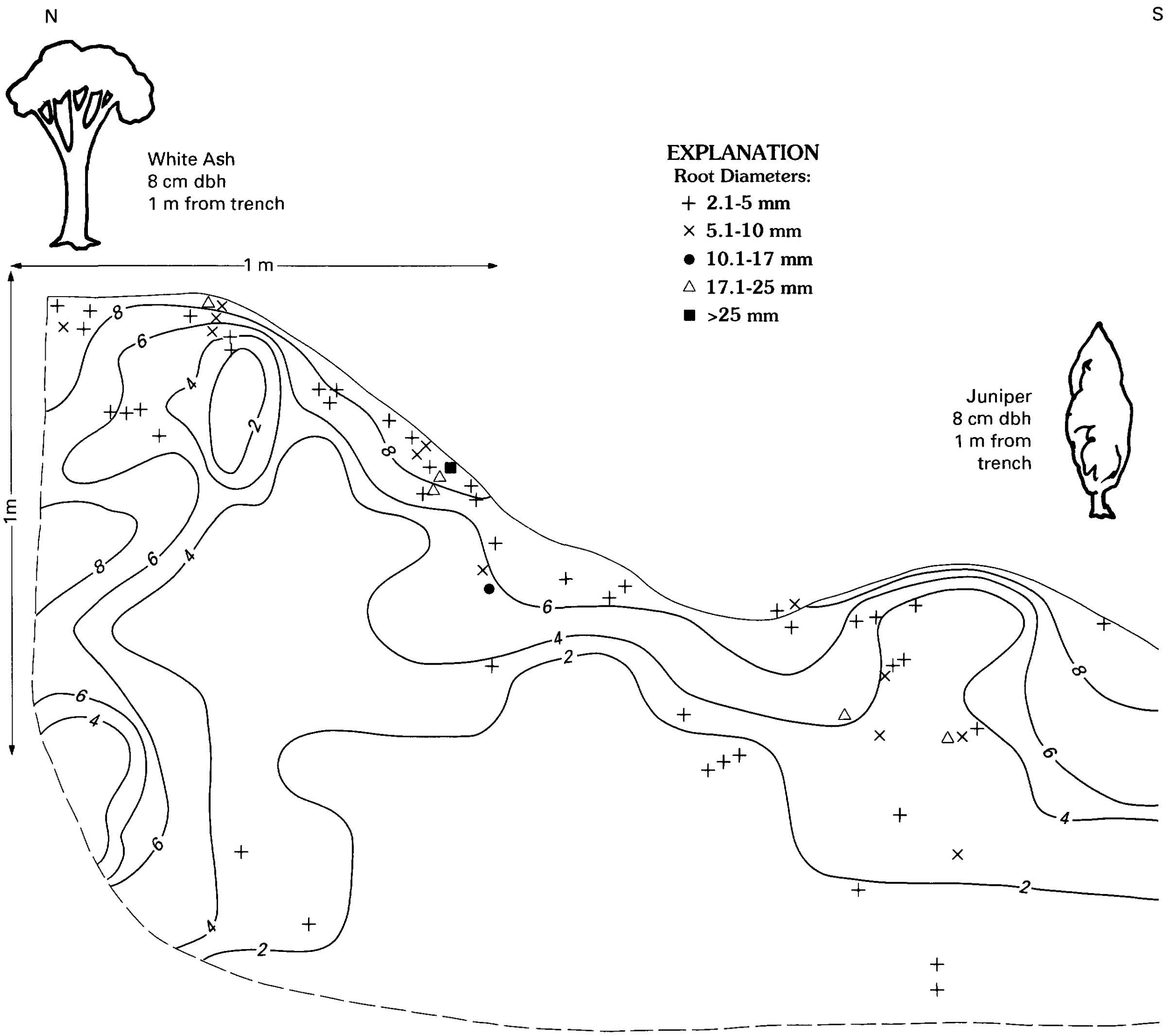


Figure 18. Density of roots in colluvium underlying a mature forest, exposed in a trench at the Delhi site. Contours show the distribution of more than 400 very small roots (<2 mm in diameter) that project through the trench face; contour values show the number of <2-mm roots in each 10×10-cm square. Larger roots (>2 mm) are shown individually by symbols representing various ranges of root diameters. The roots are most concentrated near the colluvium surface, and drastically decline in number and cross-sectional area with increasing colluvium depth. The roots project most deeply into the soil directly below individual trees. Two trees near the trench are a white ash (on the left) and a young juniper. The contour pattern under the ash tree reflects its deeply penetrating tap root. The juniper roots are concentrated near the ground surface.

between trees, if the tree is centered on the soil block. At 1-m spacing, the peak factor of safety is 2.1. With increased block surface area, the factor of safety decreases, until it approaches unity at 7-m spacing between ash trees, or 0.14 trees per meter. This is the critical spacing for ash trees of the same girth as the fully excavated tree in soil with the physical properties of the colluvium.

A spacing of 7 m between small ash trees corresponds to about 200 trees per hectare. This density compares with that of an actual mixed forest growing on a steep hillside; the hillslope at the Rapid Run site had a density of 259 trees per hectare east of the landslide and 176 trees per hectare west of the landslide. The forests were not monocultures of ash trees, of course, and other factors may have varied, but the comparison shows that the critical density calculated for ash trees is close to that observed on the stable portions of hillsides adjacent to failed areas.

CRITICAL THICKNESS OF ROOTED COLLUVIUM

Not only the spacing of trees within a soil mass affects soil stability; the number of roots and their anchoring effect

Table 1.—Stability analysis of colluvium anchored by white ash roots

[The ash tree excavated at the Spring Grove site had six roots of various diameters (as shown below) that would have projected through a plane 0.43 m below the surface. Table lists the measured pull-out resistance of roots of similar diameters that were extracted from Vermeer excavations, as a basis for estimating the resisting force and resulting factor of safety that the excavated ash tree would have provided. Two of the test roots are listed twice because they each are used to represent two of the excavated roots]

Root diameter (cm):							Total resisting force[1] (kN)	Driving force[2] (kN)	Factor of safety[3]
Excavated ash root	0.9	1.2	1.8	2.4	2.6	2.8			
Field test root	1.3	1.3	1.6	2.3	2.6	2.6			
Root number	11.22	11.22	7.22	7.20	11.13	11.13			
Displacement (cm)	Measured pull-out resistance (kN)								
0	0	0	0	0	0	0	4.27	4.3	0.99
1	.15	.15	.44	0	3.4	3.4	7.37	4.3	1.71
2	.40	.40	1.56	0	4.0	4.0	8.54	4.3	1.98
3	.40	.40	3.29	0	4.0	4.0	9.25	4.3	2.15
4	.40	.40	1.01	.33	4.0	4.0	8.44	4.3	1.96
5	.40	.40	1.58	.66	4.0	4.0	8.81	4.3	2.05
10	.18	.18	.05	2.85	3.6	3.6	8.58	4.3	1.99
20	.03	.03	0	.74	3.6	3.6	7.56	4.3	1.76
30	0	0	0	0	2.5	2.5	6.33	4.3	1.47

[1]Equals $[v(\gamma_t - \gamma_w)\cos\beta + \Sigma_{roots}\cos\alpha]\tan\phi + \Sigma_{roots}\sin\alpha + c(A)$, which, using the parameters listed below, reduces to approximately $4.27+0.41\,\Sigma_{roots}$.

[2]Equals $v(\gamma_t)\sin\beta$ = 4.3 kN (using parameters listed below).

[3]Equals resisting force/driving force.

The hypothetical block of colluvium anchored by the ash tree has the following characterisitcs:

Area (A) = 1 m^2
Volume (v) =0.43 m^3
Slope (β) = 30°
Angle of internal friction (ϕ) = 22.4°
Cohesion (c) = 2.7 kN/m^3
Unit weight of colluvium (γ_t) = 20 kN/m^3
Unit weight of water (γ_w) = 9.8 kN/m^3
Water table is at ground surface
Root angle (α) = 0°
Σ_{roots} = Sum of forces contributed by all roots

decline with depth, and, beyond some critical depth, they have no anchoring effect at all. An analysis of the factor of safety of rooted soil as a function of depth demonstrates the effect of rooting depth on slope stability. Figure 21*A* shows the effect of the root system of the excavated sugar maple 2 (Spring Grove) on colluvium at 0.5 m depth. The root configuration and density used in the analysis were derived from number, type, and orientation of roots at a given depth as indicated by the computer program DEPTH for the excavated sugar maple.

Under a normal stress equivalent to 0.5-m-thick colluvium overburden, the factor of safety for the colluvium alone would be less than one (0.90). With maple roots penetrating the colluvial soil, the peak factor of safety at 0.5 m depth is 1.01. The peak is reached at 2-cm displacement. No large roots project through the soil at greater depth.

Figure 21*B* illustrates the effect of ash roots on the factor of safety, based on data from the hand-excavated tree at Spring Grove. The ash roots penetrate deeper into the colluvium than do sugar maple roots, and so they increase soil strength at depths as great as 1 m. The initial rise in strength to its peak value is similar to that of the colluvium with sugar maple roots; it rises steeply to a peak at about 3 cm of displacement, and then diminishes with further displacement. Another peak in strength follows at 5-cm displacement, smaller in magnitude than the first peak. The patterns of force versus displacement differ with depth. The curve illustrating the anchoring by ash roots at 0.43-m depth (fig. 19) has the general shape of a category II root's force-displacement curve (fig. 7). The similarity arises because category II roots dominate at shallow depth. With increasing depth, the ash roots behave more like category I and III roots. Hence, these root categories are used in the stability analysis, and their characteristic forces sum into the relationships illustrated in figure 21 (Riestenberg, 1987).

DISCUSSION

Tree roots stabilize thin colluvium on Cincinnati's hillslopes by acting as soil anchors, which transfer shear stress at the failure surface to a stable underlying substratum. The

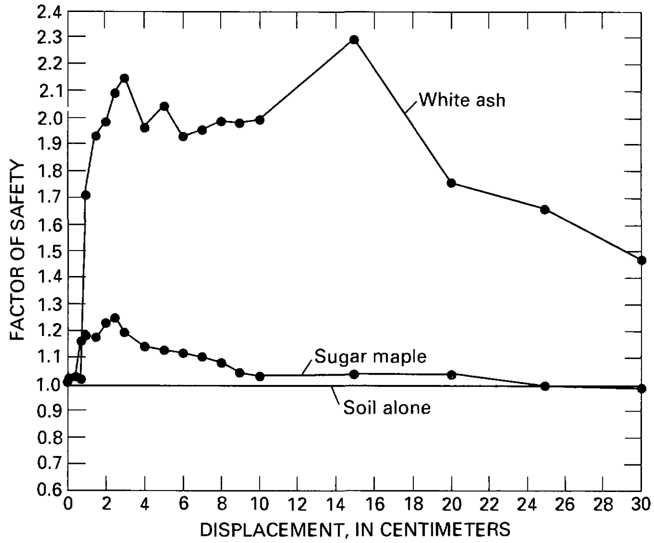


Figure 19. Stability analyses of a colluvium block inclined at 30° with and without roots. The numbers, sizes, and types of roots that project through a shear plane with an area of 1 m^2 at a depth of 0.43 m are assumed to be the same as those of one hand-excavated sugar maple or white ash trees. The factor of safety is the ratio of the resisting force to the driving force. The colluvium penetrated by ash roots develops a peak factor of safety of 2.30 (at 15 cm displacement); the colluvium penetrated by sugar maple roots reaches a peak factor of safety of 1.25. The factor of safety of fallow colluvium at 0.43 m depth is 0.99.

roots project through the soil, across the shear surface, to the weathered, fissured bedrock below. Roots are realigned at the shear surface by the movement of the overlying, failing soil. This realignment pulls the root terminus out from its preslide growth position. The root resists failure by a combination of its bond with the soil, its size, and its strength. The strength of soil can be greatly increased by the addition of root anchors. A critical spacing between root anchors may be determined for soil of different thicknesses. Small white ash trees of the same girth as those studied may be spaced 7 m from each other and anchor a hillside mantled with 0.43 m of saturated colluvial soil sloping at 30°.

The most effective root configuration has one or more deep taproots. The analysis of the anchoring effects of ash and maple shows clearly that ash trees anchor soil far better than maples. The sugar maple has as much biomass below ground as the ash but is shallow rooted and, therefore, does not penetrate to a depth at which failure is likely to occur. Neither of the sugar maples that were hand excavated for this study had roots that extend as much as 0.8 m into the soil, but the roots of the hand-excavated white ash penetrate to 1.1 m depth and would provide a factor of safety greater than 1 for a 0.8-m-thick block of soil on a 30° slope.

Maple roots do have some favorable characteristics. The sugar maple has many more category II roots than does the ash, and these roots are highly branched and resist soil shear with a continually high force as displacement progresses (fig. 7). By contrast, category I and category III roots have varying resistances with displacement. Because maple roots are shallow and highly branched, they probably reduce surficial erosion better than the sparsely branched roots of white ash; this function may not be crucial in an established forest, though, for leaf litter and understory trees could serve the purpose as well. Despite the fact that the category II roots of the sugar maple seem to be better anchors, this advantage is meaningless if they don't penetrate to depths at which landslide shear surfaces are likely to form. The ash roots are effective anchors at greater depths than maple roots simply because they are present at greater depths.

Observations of tree populations and distribution on the failed and stable portions of local hillslopes support the

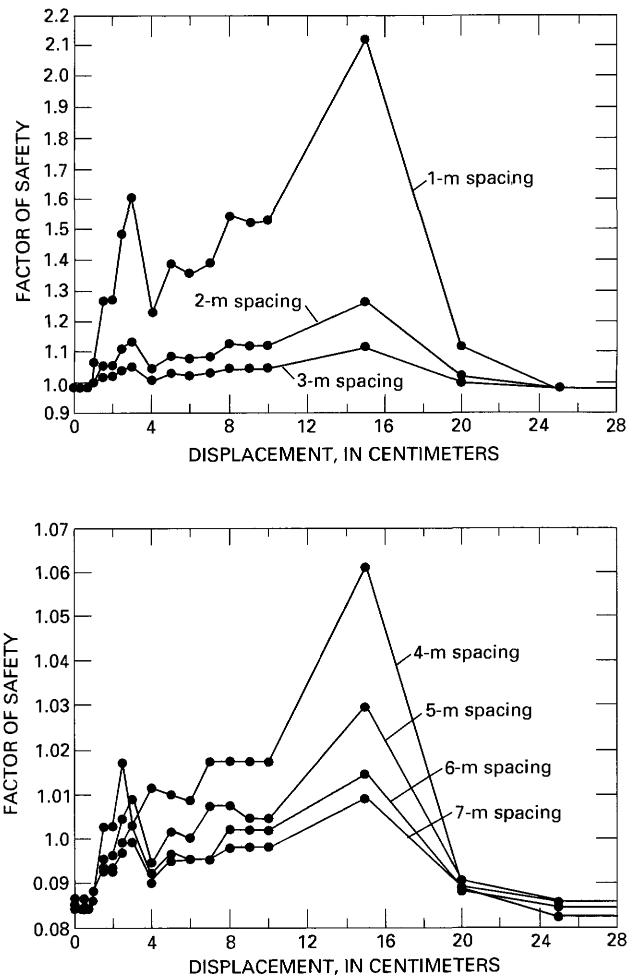


Figure 20. The effect of spacing of ash trees on stability of a hillslope. Stability analyses of a 0.43-m-thick colluvium layer supporting ash trees indicate that the factor of safety is sensitive to tree spacing. Given a slope of 30°, the critical spacing of ash trees of the size excavated at Spring Grove is 7 m, equivalent to 0.02 trees per square meter or 200 trees per hectare. The 1-m curve shown at top here differs from the top curve on figure 19 because different sets of type roots were used in generating the plots.

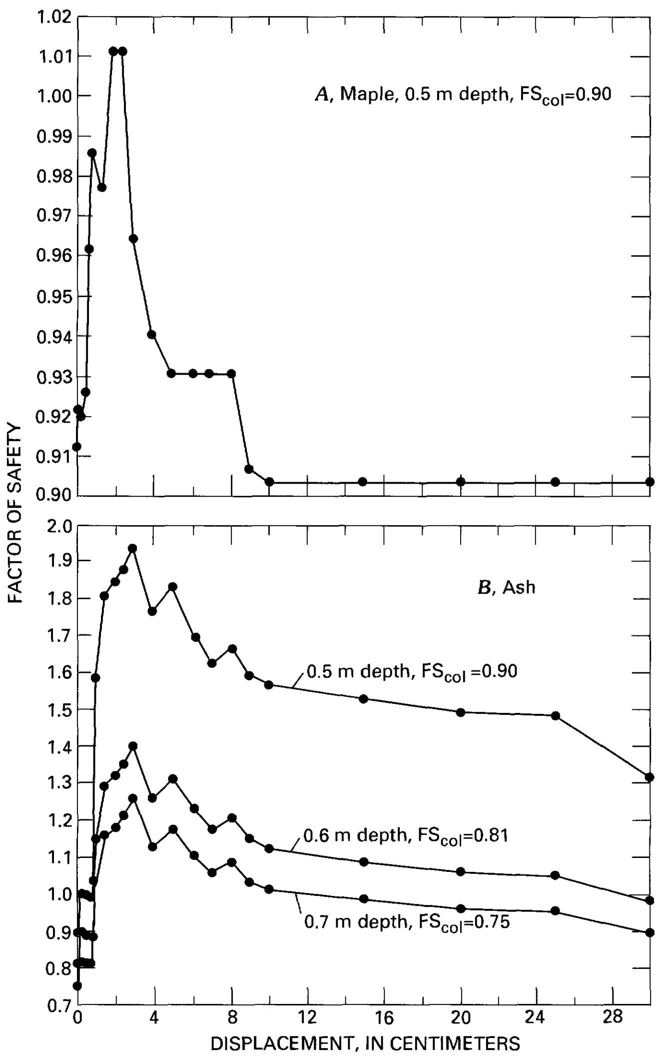


Figure 21. Factor of safety versus displacement for a 1-m^2 block of colluvium anchored at various depths by roots from a sugar maple (*A*) or an ash tree (*B*). FS_{col} is the factor of safety of fallow colluvium with no roots. At 0.5 m depth, maple roots increase the factor of safety from 0.90 at no displacement to 1.01 at 2 cm displacement. Hence, 0.5 m would be the critical thickness for the block anchored by maple roots, as the factor of safety would fall below 1 for any thicker block. Ash roots, however, could increase this factor to 1.94 at 3 cm displacement. The stabilizing effect of these roots decreases with depth as the roots become smaller and less abundant. Changes in root type with depth account for the differences in patterns of force between part *B*, above, and figure 19.

conclusions given here about critical spacing and the relative effectiveness of maples and ashes. The Rapid Run landslide (Riestenberg and Sovonick-Dunford, 1983) averaged 0.5 m in thickness and supported a monoculture of sugar maples. These maples had girths similar to those of the two that were excavated by hand. Maples of this girth are nominally able to anchor soil as much as 0.5 m thick, but only if they are closely enough spaced. The density of trees on the landslide mass was about one-half that of trees in the stable forested area adjacent to the landslide. The spacing of the trees on the stable portion of the hillslope averaged 7 m, the same as the critical spacing calculated for the ash tree on soil 0.43 m in thickness. The maple trees on the landslide were so widely spaced that they exceeded even the critical spacing calculated for the more deeply rooted white ash. Hence, the landslide was probably inevitable.

A limitation of this study is that it analyzes the root systems of trees of relatively small girth. Larger trees were not studied for reasons stated earlier in the text, but one may make certain assumptions about the root systems of larger trees from observations made at trench faces and exposures along streams. Roots are most concentrated within the uppermost 0.5 m of soil, taper in numbers to about 0.8 m, then fall off abruptly in numbers and become sparsely distributed and smaller in girth at greater depths.

With knowledge of the distribution of roots for a species and the pull-out resistance from the soil, one can calculate the resistance offered by a root system to failure. But trees also can stabilize the soil by reducing the moisture content of the soil through transpiration during the growing season. The timing of Cincinnati's landslides may reflect the stabilizing effect that transpiration has on hillslopes. They occur in late winter and in early spring before leaf-out. By summertime, when the field tests of the roots' pull-out resistance were done, the soil is normally drier and more stable than in the spring. To restore springlike moisture conditions, the field site was continuously watered throughout the testing period.

The effectiveness of roots in stabilizing a hillslope depends upon the displacement of soil that can be tolerated at a given site. The roots' resistance to failure peaks at about 3–4 cm of soil displacement. This displacement may be allowable in some areas, such as on hillslopes where the soil is thin and engineering structures are anchored in bedrock, but not in other areas where damage to structures will occur at small displacements.

A tree species selected for stabilization of a hillslope must have strong roots which penetrate deeply into the soil; the species must have the potential to thrive in the local climate and soil, and to tolerate competition with local biota. A species with the above characteristics as well as a high rate of transpiration would be ideal for stabilization of shallow soil. Trees may be combined with engineering materials in some cases to produce an inexpensive, attractive means of hillslope protection (Gray and Leiser, 1982).

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