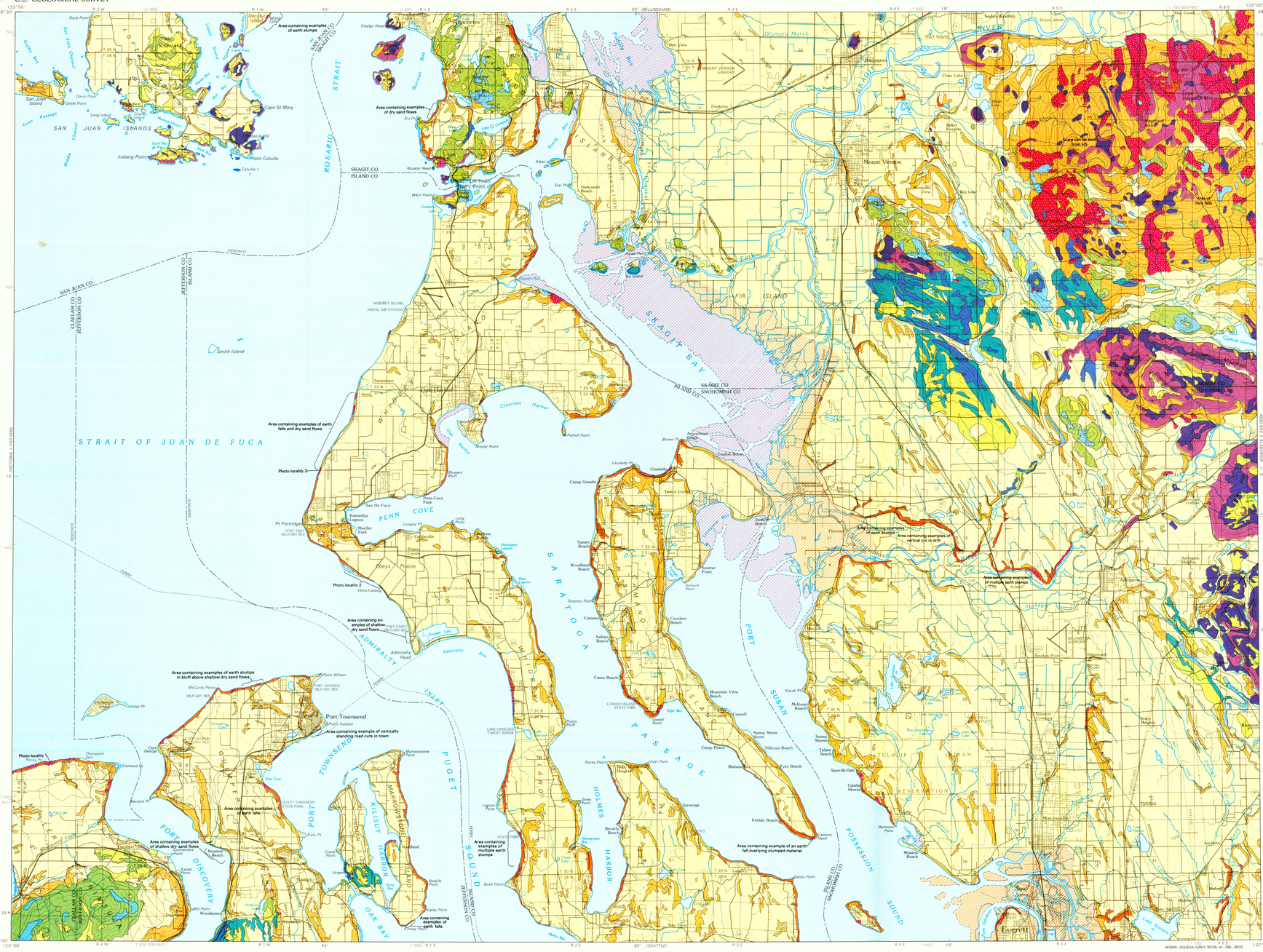
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

FOLIO OF THE
PORT TOWNSEND QUADRANGLE, WASHINGTON
MAP I–1198–C



Base from U.S. Geological Survey, 1975
10,000-foot grid based on Washington coordinate system, north zone

SCALE 1:100 000

CONTOUR INTERVAL 50 METERS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

Interpretation based principally on unpublished data provided by Fred Pessl, Jr., D.P. Dethier, and J.P. Minard (written commun., 1980–81), on the Washington State Department of Ecology, "Coastal Zone Atlas of Washington" (1978a–c, 1979a–c), and on the natural-slope map compiled by Frederick (1979).

EXPLANATION OF MAP UNITS

SLOPE-STABILITY UNITS ON SURFICIAL MATERIALS

CLASS 1—Slopes are generally low, less than 15 percent. They are underlain commonly by sandy or gravelly deposits or by hard glacial till on gently rolling uplands. Those slopes underlain by silty or clayey beds are considered to be class 1 only where surfaces are nearly flat. Class 1 slopes can be unstable where deeply excavated into materials underlying the hard till; in such cases, excavation walls can collapse. Some class 1 slopes on tidal flats and river valleys may be susceptible to failure from liquefaction during strong earthquakes

CLASS 2—Slopes range from 15 to 30 percent; locally, can be steeper than 30 percent in the mountains and along sea cliffs. Commonly underlain by nearly impermeable till or permeable, granular sandy or gravelly deposits. Steep, normally stable slopes along sea bluffs can fail due to wave erosion during storms or to placement of septic systems or outfalls for surface drainage

CLASS 3—Slopes are commonly steeper than 15 percent, and in places steeper than 40 percent (in places nearly vertical). Generally underlain by (a) silt, clay, or fine sand; (b) nearly impermeable till; or (c) loose permeable sand and gravel that is generally overlain by nearly impermeable deposits. Such permeable sand and gravel (outwash or sand layers in clay-rich sediments) beneath the hard glacial deposits can provide channels for ground water, which can lead to internal erosion and slope failure

AREAS OF POTENTIAL LIQUEFACTION—Slopes potentially susceptible to failure by liquefaction from shaking during earthquakes; underlain by wet, fine-grained materials containing confined beds or layers of saturated fine-grained materials. Locally contains small areas overlain by d: pools of landfill not shown on map. Overprint on map extends from shore marked by mean high tide to edge of tidal deposits at mean low tide. Overprint on map extends shoreward over deposits that may have various stability classifications but in turn be underlain by liquefaction-susceptible deposits

OLD DEPOSITS FROM SLOPE MOVEMENT—Underlie areas that may encompass several slope-stability classes. Generally stable now, but stability could change with modification of climate or land use

CONTACT—Approximately located; dashes represent approximate margin of tidal deposits at mean low tide as derived from aerial photographs; tidal deposits are exposed between daily high tides

SLOPE-STABILITY UNITS ON BEDROCK

Most stable

CLASS I—Slopes are generally less than 15 percent. Slopes are underlain by bedrock that ranges from competent, homogeneous rock to less competent, layered rock that may be weathered, may be locally deformed, or may include numerous weak layers. Slopes tend to be stable unless oversteepened by deep excavations or encroached upon by headward erosion from adjacent steeper slopes

CLASS II—Slopes are generally steeper than 15 percent but less than 30 percent. Generally underlain by competent to very competent rocks that range from those that have variability in internal structure and composition to those that are nearly homogeneous

CLASS III—Slopes are generally steeper than 15 percent but less than 30 percent. Underlain by thin-bedded, incompetent sedimentary rocks. Slopes are susceptible to earth slumps or flows from excessive rainfall or soaking

CLASS IV—Slopes are generally steeper than 30 percent. Commonly underlain by the same competent rocks that underlie Class II slopes

CLASS V—Slopes are generally steeper than 30 percent and may be nearly vertical along river gorges and sea cliffs. Excavations and stream erosion can truncate bedding planes and make slopes unstable. Underlain by the same thin-bedded and incompetent sedimentary rocks that underlie class III slopes

CLASS VI—Slopes are steeper than 15 percent. Excavations, erosion, and excessive moisture can cause ground to become unstable and to move. Generally underlain by fine-grained or thin-bedded sedimentary rock and by intensely deformed, foliated and fractured metamorphic rocks containing layers of weak, slippery materials (such as serpentine or micaceous schist) and numerous planes of weakness

CLASS VII—Slopes are generally steeper than 30 percent, in places nearly vertical, especially along stream gorges and sea cliffs. Instability tends to increase with steepness; the steepest slopes are extremely unstable and easily disturbed by works of man or by natural events; cliffs are susceptible to undercutting, and rock falls and rock slides can occur. Generally underlain by the same weak rocks that underlie class VI slopes

Least stable

INTRODUCTION

This map is one of a series made by the U.S. Geological Survey to assist in land-use planning, resource management, and environmental protection in the Puget Sound region. Our study of the Port Townsend quadrangle attempts to identify different degrees of slope stability, or instability, as a step in the process of making effective policies for land use.

As population growth in the Puget Sound region forces greater utilization of less-than-ideal sites for development, losses due to slope failure will increase. Planning and management decisions that can minimize future economic losses and hazardous conditions related to slope failure require regional and local geologic studies to determine slope-stability characteristics. This map is intended to provide slope-stability information on a regional basis for planners, consultants, developers and others interested in wise use of the land. It is not intended as a detailed delineation of all stable or potentially unstable slopes. Instead, it is intended to provide a general outline of slope conditions that may warrant closer examination prior to changes in land use.

Slope stability is classified in this report according to the relative susceptibility of land in the quadrangle to failure by any one of several downslope movements. Slope failures are caused by changes in natural or in artificial conditions, or in both, and result from the complex interaction of geology, topography, climate and, often, human activities. Ground movements commonly associated with slope failure may be described as falls, slides, flows, or a combination of these movements (Varnes, 1978, p. 12–22).

The total financial loss due to slope failures is probably greater than that due to any other single geologic hazard (Schuster, 1978, p. 2). Although such failures usually are less impressive than are major floods, strong earthquakes, or volcanic eruptions, they are widespread and occur relatively frequently. Damage costs due to slope failures include direct costs, such as those associated with actual damage to installations and property, and indirect costs, such as reduced real estate values and tax revenues for land damaged or threatened by slope movements, loss of productivity from slide-affected lands, and a variety of economic losses due to slide-damaged transportation and utility systems. Estimated total costs, both direct and indirect, due to slope failure in the United States exceed $1 billion per year (Schuster, 1978, p. 3). Very few studies of costs of slope-failure damage have been done for limited geographic areas like the Port Townsend quadrangle, but two studies of damage in Washington for 1972 revealed direct and indirect costs of about $5.6 million for Washington's state transportation system and about $250,000 from 80 slope failures in western King County, 56 km south of this quadrangle (Coombs, 1974, p. II-1; Tubbs, 1974).

METHOD OF MAP PREPARATION

Preparation of this map entailed classification of slopes based on steepness, followed by an evaluation of the types of underlying geologic materials with respect to their impact on slope stability.

A map at a scale of 1:100,000 showing natural slopes (Frederick, 1979) was used as a base on which to outline areas having slopes less than 15 percent, slopes between 15 and 30 percent, and slopes steeper than 30 percent (fig. 1). The selection of 15 percent for use on this map as the critical slope angle between stable and potentially unstable slopes is based on past experience in nearby areas (Miller, 1973) and on the experience of others (Nilson, Taylor, and Brabb, 1976). We added detailed slope changes in some areas depicted on the natural slope map as being less than 15 percent because the contour interval of 50 m included some steeper slopes within those areas. To make these refinements, the lowland region was reexamined using larger scale topographic maps having smaller contour intervals (1:24,000 with 10-, 20-, or 40-ft contour intervals; 1:62,500 with 50-ft contour intervals). Areas on these maps having slopes steeper than 15 percent were outlined on the 1:100,000-scale map, within the constraints of the map scale, in order to produce a modified slope map. Geologic data were then considered to help determine the relative slope stability of the land surface in the Port Townsend quadrangle. Other factors that might be significant, such as locally intense precipitation, dip of geologic beds, and slope direction, were not evaluated.

Data on the distribution and sequence of deposits of unconsolidated materials was provided by Fred Pessl, Jr., D. P. Dethier, and J. P. Minard (written commun., 1980–81). Such information was supplemented by field data collected by the senior author for a study of physical properties in the Port Townsend quadrangle. Locally, larger scale geologic maps (Danner, 1957; Whetten, Dethier, and Carroll, 1979; Dethier and Whetten, 1980; Minard, 1980 a–f; Whetten, 1980) were used to clarify stratigraphic details of the surficial deposits.

Table 1.—*Classification of relative slope stability based on slope and on underlying surficial materials and bedrock. Stability classes are numbered according to degrees of relative stability: class 1 and class I are most stable*

Underlying material	Slope (percent)		
	0 – 15	15 – 30	>30
Surficial deposits	Class 1 All surficial deposits	Class 2 Coarse granular deposits (including till) Class 3 Fine-grained sand, silt, and clay	
Bedrock	Class I All bedrock types	Class II Massive, competent bedrock Class III Thin-bedded sedimentary bedrock Class VI Fine-grained, layered, fractured bedrock	Class IV Class V Class VII

Ten classes of relative slope-stability are shown on this map. Three of these classes (arabic numerals) indicate relative stability of slopes (1) in terrain underlain by surficial materials, but where slopes are not reflected by the 50-m contour interval of this map, or (2) that are thick deposits of glacial materials or soil within areas mapped as bedrock on the source maps from which compilation was made. Table 1 summarizes the relative slope-stability classification on which this map is based.

Surficial materials in the lowland part of the quadrangle are predominantly glacial deposits and younger alluvial deposits. Physical characteristics, such as firmness and compactness, are generally consistent throughout the quadrangle. These deposits can be subdivided according to the predominant particle sizes (texture) into coarse-grained deposits (principally sand, gravel, and till—hardpan) and fine-grained deposits (fine sand, silt, and clay). Combining textural subdivisions of the surficial deposits with the selected slope intervals (0–15 percent, 15–30 percent, >30 percent) results in three relative-slope-stability classes (table 1). Slope-stability classification along the bluffs, however, was evaluated in terms of steepness and the presence or absence of fine-grained deposits that impede downward flow of moisture and (or) coarser grained granular deposits that transport moisture; such conditions reduce stability.

The classification of slopes underlain predominantly by bedrock is based on geologic data provided by J. T. Whetten, D. P. Dethier, and P. R. Carroll, written commun., 1980). The bedrock units were subsequently classified according to relative-stability characteristics such as rock type, mineral composition, bedrock attitude, type of layering, and homogeneity (P. R. Carroll, written commun., 1980). Taking this classification, the bedrock units were then placed into three relative-stability groups. Selected slope intervals (0–15 percent, 15–30 percent, >30 percent) were combined with the three stability groups to define seven classes of relative slope stability for the bedrock areas (roman numerals, table 1). The bedrock terrain also contains areas of thin (less than 3 m), discontinuous blankets of unconsolidated materials.

FACTORS INFLUENCING SLOPE STABILITY

Two general factors influence slope stability—inherent and external. The inherent factors, such as the general steepness of slopes and the types and interrelation of geologic materials, tend to determine the location of potentially unstable slopes. External factors, such as erosion, addition of moisture, and man's activities tend to determine the timing and frequency of slope failures. In the Puget Sound lowland, the addition of moisture, most commonly by rainfall, generally is the variable that most effectively can reduce stability. Next in importance in causing instability is erosion by rivers and streams whose waters impinge against and undercut the embankments bounding the channels. However, along the marine shorelines wave and tidal erosion can be crucial.

The character of geologic materials in this area critically influences the relative stability of slopes of similar steepness. Most of the geologic materials in the quadrangle are flat-lying to gently inclined glacial or alluvial deposits. The composition and physical characteristics of such deposits vary greatly, both laterally and vertically. Of particular importance is the occurrence of relatively impermeable materials, such as silt or clay, beneath or within more permeable materials, such as sand or gravel. Water moving through these materials can saturate those which are permeable (sand or gravel) and be impeded by beds which are impermeable (silt or clay). The result may cause springs to flow from a hillside near the contact between the sand and clay, or may saturate the thin, overlying soil that blankets the slopes, or may saturate the sand above the silt and clay. Such saturation may cause the materials to lose cohesion and move downslope.

Much of the Puget Sound lowland is underlain by glacial till or glaciomarine drift. The till is firm at depths below 1–3 m, but the uppermost part is weathered and loose. Moisture during the rainy season moves easily through the weathered drift but is impeded by the firmer, underlying unweathered material. Consequently, the upper part of the till beneath the slopes can be saturated. In fact, swamps and wet boggy areas on the drift are common (Minard, 1980a–f).

Geologic relationships involving bedrock are also important to the stability of a slope. Bedrock forms steep, normally stable slopes along some of the bluffs bounding mainland stream valleys and along the coast (classes IV–V); it also forms slopes of variable steepness in the mountains in the eastern part of the quadrangle (classes I–VII). Soil and slope debris overlying the rock may be loose, permeable, and unstable, but the underlying rock is not. As a result, the soil and debris can move downward over the surface of the rock along which the flow of water is concentrated. Deep-seated slides involving large amounts of bedrock are relatively rare. However, in the northeastern part of the quadrangle, bedrock slides are more abundant than elsewhere. One slide, on the southwest side of Cultus Mountain (fig. 5), is estimated to have displaced about 20 million cubic meters of rock another slide, west of Bald Mountain, displaced about 100 million cubic meters of rock (D. P. Dethier, unpub. data, 1981).

Two other factors affecting slope movement are not evaluated on this map. No attempt is made to determine or depict the effect of slope-failure debris encroaching upon flat, stable surfaces from unstable slopes uphill; sites along the base of slopes mapped as class 3 and class V–VII should be evaluated for this potential condition. Also, no assessment is made of the stability of manmade cuts and fills.

APPLICATIONS OF SLOPE-STABILITY INFORMATION TO LAND-USE PLANNING AND RESOURCE MANAGEMENT

Loss-reduction measures concerned with potential slope failure are being increasingly applied as part of land-use planning and resource management policies. Such measures include a combination of geologic investigation, engineering practice, and effective enforcement of regulatory ordinances. An example of one of the few municipalities that enacted some type of loss-reduction measures is Los Angeles, where relatively weak bedrock and prevalent steep slopes cause widespread slope instability. The enactment of a municipal grading ordinance in 1952, followed by major revisions of the ordinance in 1963, resulted in a significant decrease in economic losses associated with slope failure. Following torrential rains during 1969 that caused much damage in this area, studies showed that sites developed before 1952 reflected an average damage cost of $330 per developed hillside lot (10,000 sites) and that slope failure occurred on 10.4 percent of the lots. Sites developed after 1963, complying with a comprehensive grading ordinance that requires soils engineering and engineering geologic evaluation during both design and construction stages, showed an average damage cost of $7 per lot (11,000 sites) and a slope-failure incidence of 0.13 percent (Slossen, 1969, p. 9, table 1).

In western King County, Wash., 56 km south of the Port Townsend quadrangle, slope movement hazards are included in County Ordinance 4365, which establishes criteria for identifying lands subject to natural hazards and lands supporting unique, fragile, or valuable natural features. Ordinance 4365 also establishes a process for regulating development within the designated areas. Areas having severe slide potential are mapped as part of the technical basis for grading, building, foundation design, housing-density, and other land-development regulations (Department of Planning and Community Development, King County, Wash., 1980).

Potential slope instability has also been recognized as an important consideration in evaluating plans for pipeline routes in the Puget Sound region. Slope failures are considered natural hazards that could cause pipeline rupture during construction and subsequent operation of a proposed crude-oil transportation system in the central Puget Sound region. Mitigating measures, such as rerouting the pipeline to avoid potentially unstable slopes and using stronger pipe in unavoidable areas of potential slope failure, are considered to be as much as 85–95 percent effective in reducing damage to the pipeline because of slope instability (U.S. Bureau of Land Management, 1979, p. 4–1).

Damage associated with slope failure, however, is not limited to dramatic rock-falls, sea-cliff collapse by earth-falls, or large-scale debris slides; relatively small, inconspicuous downslope movements can make homes unlivable, structures unsafe, and utility and other forms of transportation networks expensive to maintain. Such hardship and economic loss can be significantly reduced by avoiding slide-prone areas. Damage can also be reduced by identifying and avoiding human activities that contribute to slope instability. Such activities include unnecessary soaking of the ground, excavations at the toes of slide deposits, and activities that increase erosion near the base of slopes, such as removal of vegetation, careless grading, and excavation. In some situations land can be stabilized to some extent by specially engineered retaining walls and other structures, by dewatering, or even by removal of a landslide mass. However, unless the land is especially valuable, economic considerations may dictate avoiding unstable areas for intensive land uses.

Wise resource management policies, which consider long-range cost effectiveness and health and safety, are becoming increasingly important in the Puget Sound region as the development of natural resources steadily expands to include marginally suited land and specialized, sensitive environments. Geologic data that identify significant geologic conditions, such as potential slope instability, provide the essential technical foundation upon which realistic, justifiable regulations, policies and ordinances can be based. Similarly, detected geologic data provide the basic technical input to the formulation of engineering practices designed to avoid or reduce undesirable effects of proposed activities and installations. The information provided by this map and text should help to identify areas of potential regional concern and to guide detailed studies.

TYPES OF GROUND FAILURES

Earth material that moves as a result of instability is commonly called a landslide. Varnes (1978, p. 11) prefers to replace that usage with the term slope movement, and that more precise description is applied in this study of the Port Townsend quadrangle to (1) earth falls, (2) earth flows, (3) shallow dry-sand flows, (4) earth slumps, (5) dry-sand flows, (6) debris slides and flows, (7) rock slides, (8) rock falls, and (9) soil creep. The first five types are found in the lowland areas, whereas the debris slides and flows and rock slides and falls are found almost exclusively in the mountains in the northeastern part of the Port Townsend quadrangle. Soil creep occurs throughout the areas in the uppermost part of surficial deposits, which include the weathered mantle overlying bedrock. Most of the potentially least stable ground occurs along the sea bluffs, river and stream channels, and older abandoned channels related to deglaciation of the Puget Sound lowland.

Slope failures are distinguished partly on the basis of moisture content and rate of movement. Terms in this study follow Varnes (1978, p. 24), who defines moisture content relative to the materials involved in slope movements as "***"(a) dry, contains no visible moisture; (b) moist, contains some water but no free water and may behave as a plastic solid but not as a liquid; (c) wet, contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water; and (d) very wet, contains enough water to flow as a liquid under low gradients." Rates of movement used to help describe different types of slope failures are shown in figure 2.

Earth falls (fig. 3) characteristically occur along steep bluffs composed of glacial drift and are the most abundant type of slope failure in the lowland part of the quadrangle. The many miles of shoreline of the peninsulas and islands contain nearly continuous sea cliffs and steep bluffs that are periodically subjected to storm action and seasonal erosion by waves and tides. Such erosion removes the base of the steep slopes, undercuts the overlying materials, and thereby creates situations that allow the restraining shear strengths of the overlying drift to be exceeded and the material to fall freely as large blocks or as many small ones. Such failures commonly extend to the top of the bluffs. Class 2 and class 3 slopes are susceptible to such failures.

Rock falls are like earth falls except that rock fragments are involved in the failure. Such failures apparently occur where steep bedding, jointing, or foliation planes are weak, and the shear strength is exceeded. The mass falls freely, fragments subsequently can bound a considerable distance downslope over the ground or can evolve into debris slides or flows.

Earth flows (fig. 4) generally consist of clay-rich mixtures of fine soil. In the Port Townsend quadrangle, earth flows are typically wet to very wet depending on the moisture content; such flows exist along bluffs underlain by silt and clayey silt, glacial drift, or, rarely, sandy outwash, and along highway and railroad cuts, especially on the shady sides of the cuts during thaws. Earth flows in the Puget Sound region are most common in glacial till or silt and clay.

Shallow dry-sand flows (fig. 5; Varnes, 1978, p. 20, fig. 2.25), sheetlike flows of sand, and the thicker dry-sand flows (fig. 6) occur principally along sea bluffs where sand or sandy gravel (a) completely underlies the slopes, (b) underlies the upper parts of bluffs that are supported by harder or firmer sand or silt, or by compact glacial drift at the base, or (c) underlies a surface deposit of firm till. The firmer supporting material may be partially obscured by the shallow sand flow. Wave erosion generally causes the uppermost skin of material to flow downward as a shallow flow. The largest dry-sand flows can encompass broad areas along the bluffs, and can form alcoves that encroach hundreds of meters back from the bluff edge. The sand flows through channels eroded into the more compact underlying deposits and accumulates as a fanlike apron along the lower part of the sea bluff or on the beach. Because the geologic sequence continues laterally along the bluffs, such slides can result in a series of scallopline alcoves extending along the margin of the sea bluff. It is not unusual to find manmade structures constructed on the fingerlike projections of undisturbed ground that separates the alcoves in the slide areas. Class 3 slopes can develop such slides, and class 1 slopes can be encroached upon as the margins of the alcoves enlarge landward.

Earth slumps (fig. 7) fail along internal slip surfaces, and the movement has a rotational component. The head of a slump is characterized by a near-vertical scarp, the toe of a slump commonly contains bulges and transverse ridges that may disintegrate into an earth flow. Slumps are less common than earth flows or shallow dry-sand flows; however, the sea bluffs and river bluffs provide slopes suitable for slumps. In a typical slump, the base of the bluff contains fine-grained materials, such as silt or clay, immediately overlain by more coarse-grained and permeable deposits. Firmer deposits of glacial drift generally cap this sequence of materials at the top of the sea or river bluff. Slumps are most common on class 3 slopes, but can occur on class 2 slopes as well, as a result of either natural or manmade disturbances.

Debris slides (fig. 8) and flows (figs. 9, 10) underlie most of the landslide areas in the mountains in the northeastern part of the quadrangle. Most of the slide areas shown are old, some probably dating to the retreat of the lowland ice sheet, and most are currently stable. Many of these areas underlie class 2 slopes. A well-integrated drainage is typical of these slides, and attests to their age; only locally are there slides without integrated drainage. Recent failures are most common where glacial drift underlies uneven terrain containing steep slopes; such failures also are common on class III and class V slopes that are underlain by layering or jointing more or less parallel to the slopes and truncated by human activity or natural erosion. Increased land use in the mountains can entail deep roadcuts and accelerated forestry practice, which can reduce rock-system stability, steepen support and change the character of the slope hydrology, which in turn could reduce the stability of steep slopes and induce failure following high rainfall or snowmelt periods (Swanston, 1967, 1969, 1970; Gray, 1970; Bailey, 1971; Swanson and Dryness, 1975).

Glacial drift constitutes most of the debris in the slides; however, large bedrock fragments locally are incorporated in them, especially in slides that originated in areas underlain by incompetent rock.

Small areas of modern debris slides and flows occur in a few places in the quadrangle. Some are in the tributary valleys in the mountainous area, and some are along the north bluffs of the Stillaguamish River. In general, these slides cover only limited areas in small ravines or on slopes that were locally saturated by heavy rainfall.

Failures in the mountainous areas, where planes of weakness that are more or less parallel to the slope are truncated by works of man or by natural erosion, generally consist of rock-block slides or rock slides (fig. 11). Such failures account for only a small percentage of slope movements in the mountains, but they can occur on class III and class V slopes.

Soil creep (fig. 12) occurs as widespread but seldom recognized land movement on class 2 and class 3 slopes in the lowland, and on class II–VII slopes in the mountains. Creep is deformation that continues under constant stress (Varnes, 1978, p. 17), and it can occur in bedrock as well as in unconsolidated materials (that is, soil, in an engineering sense). Because creep does not leave recognizable large scarps or alcoves, field examination is required to locate specific areas of creep. Tilted tree trunks and slightly uneven turf on tree-free slopes may indicate downslope movement by creep.

Failure of saturated deposits beneath nearly flat-lying slopes can occur in parts of the Port Townsend quadrangle by liquefaction as a result of shaking during earthquakes. Such failures have, historically, occurred in loose, wet, clay-free, fine-grained granular materials (Youd and others, 1975, p. A68; Keefer, 1981). Liquefaction is defined as the transformation of such a granular material from a solid state into a liquefied state as a consequence of increased pore pressure (Youd, 1973, p. 3). The act of transformation does not necessarily require ground failure, but ground failure is a common consequence.

Large areas underlain by wet to saturated, loose, fine-grained granular materials are shown on the map by a pattern and are considered susceptible to failure as a result of liquefaction. The susceptible areas are principally the tidal flats and tidal swamps and the lower parts of river valleys. These areas contain geologically young, fine-grained alluvial deposits that extend from the surface downward to beneath the water table, or saturated, silt-free sandy deposits within tight, finer grained deposits below the water table (Frank, 1980).

Failures commonly associated with liquefaction are flowage, lateral spreading (fig. 13), and the fracturing of ground and ejection of sediment and water as sand boils from saturated and confined sand layers. Flowage can result from liquefaction induced by exceptional rainfall; lateral spreading and sediment ejection, as well as flowage, are most commonly associated with liquefaction during earthquakes, commonly on very gentle slopes—slopes as low as 1.5 percent, or 0.9° (Youd, 1973, p. 9). All of the tidal flats, swamps, and river valleys shown on the map by the pattern contain the slope and subsurface geologic conditions suitable for potential ground failure during earthquakes.

Another effect of liquefaction during earthquake shaking is the possible loss of foundation support of manmade structures. In severe cases of liquefaction, such structures can sink into the liquefied materials, and buried tanks can float to the surface. Development of susceptible areas requires understanding of potential problems and careful investigation of the local ground conditions.

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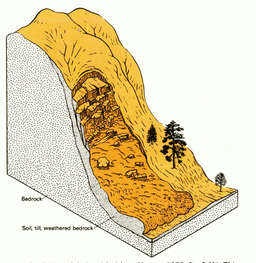

Figure 1.—Steepness of slopes in percent and degrees. Percentage is determined by dividing the vertical distance (v) by the horizontal distance (h) and then multiplying by 100.

Figure 3.—Earth fall along north-facing bluff, vicinity of Rocky Point, Miller Peninsula, south shore of Strait of Juan De Fuca. Firm glacial drift detaches from a nearly vertical slope of cliff and descends principally by falling through the air. Undercutting by flowing water and removal of coarse alluvial deposits is the principal cause of this type of instability. There is little warning, other than raveling of small pieces of debris or stones, of this type of impending failure. Photo locality 1. Photograph by Fred Pessl, Jr., U.S. Geological Survey.

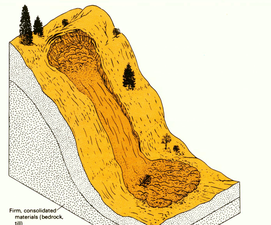

Figure 4.—Earth flow (modified from Varnes, 1978, fig. 2.1r13). Earth flows consist of clay-rich mixtures of unconsolidated material and are a result of increased water content from either natural or manmade causes. Rate of movement ranges from slow to rapid.

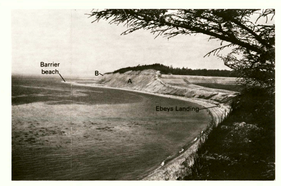

Figure 5.—Shallow dry-sand flow (Varnes, 1978, p. 20, fig. 2.25) on east side of Admiralty Inlet to Puget Sound, Whidbey Island. This form of earth flow is dry and consists almost exclusively of sand. It occurs on slopes underlain by loose sand or gravelly sand, generally glacial outwash, lying at or near the angle of repose. Wave and water erosion along the seashore causes slopes periodically to become unstable and allows materials to flow toward the beach. Location A is underlain by a shallow dry-sand flow stabilized by vegetation as a result of shore protection by an offshore barrier beach. A change in longshore currents caused by modification of the shoreline by man could result in removal of the barrier beach and resumption of erosion of the sandy slope. Location B is a slope underlain by a shallow dry-sand flow that is not stabilized and periodically flows as a result of shore erosion. Photo locality 2.

**Figure 6.—Dry-sand flows (Varnes, 1978, fig. 2.1r4) on bluff about 7 km northeast of Point Partridge, northwestern Whidbey Island. This form of earth flow occurs along sea bluffs in localities where thick (more than 10m) loose sand or gravelly sand overlies older, more compact silt, sand, or glacial drift. Recessional outwash is generally the source of the loose sand. The flow moves rapidly to very rapidly. After heavy rains or snowmelt, wet-sand flows can replace normally dry flows. Sand can flow from beneath firmer drift at the top of a bluff, which permits soil or earth falls, as well as sand flows, to move the bluff line landward. Manmade structures near such a