Chapter 4

Field Investigation

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The field investigation is the central and decisive part of a study of landslides and landslide-prone areas (*4.9*). The investigation serves two essential purposes: (a) to identify areas subject to sliding when future construction is being planned and (b) to define features of and environmental factors involved in an existing slide. Unstable areas prone to sliding usually exhibit symptoms of past movement and incipient failure; most of these can be identified in a detailed field investigation before design. Such investigations can show how to prevent or at least minimize future movements, and they can suggest alternate routes that are less likely to slide. Once a landslide has developed (either before the construction of a facility or after work is under way), the investigation is made to diagnose the factors responsible for the movement and to determine what corrective measures are appropriate to prevent or minimize continuing movements.

Because landslides are continually changing phenomena, the field investigation cannot be considered an isolated or easily defined activity; instead, it is iterative. New data generate new questions that require more data for answers. Although the investigation must continue for a period of time consistent with the shifting topography and changing environment, it is constrained by the timely needs for preventive or corrective design. Thus, field investigations should commence long before construction is anticipated and sometimes continue long after the area has been changed by the anticipated construction.

SCOPE OF FIELD INVESTIGATIONS

A number of features require study in a field investigation; these are enumerated below as a checklist for planning a study.

I. Topography
   A. Contour map
      1. Land form
      2. Anomalous patterns (jumbled, scarps, bulges)
   B. Surface drainage
      1. Continuous
      2. Intermittent
   C. Profiles of slope
      1. Correlate with geology (II)
      2. Correlate with contour map (IA)
   D. Topographic changes
      1. Rate of change by time
      2. Correlate with groundwater (III), weather (IV), and vibration (V)

II. Geology
   A. Formations at site
      1. Sequence of formations
      2. Colluvium
         a. Bedrock contact
         b. Residual soil
      3. Formations with bad experience
      4. Rock minerals susceptible to alteration
   B. Structure: three-dimensional geometry
      1. Stratification
      2. Folding
      3. Strike and dip of bedding or foliation
         a. Changes in strike and dip
         b. Relation to slope and slide
      4. Strike and dip of joints with relation to slope
      5. Faults, breccia, and shear zones with relation to slope and slide
   C. Weathering
      1. Character (chemical, mechanical, and solution)
      2. Depth (uniform or variable)

III. Groundwater
   A. Piezometric levels within slope
      1. Normal
      2. Perched levels, relation to formations and structure

3. Artesian pressures, relation to formations and structure

B. Variations in piezometric levels–correlate with weather (IV), vibration (V), and history of slope changes (VI)
1. Response to rainfall
2. Seasonal fluctuations
3. Year-to-year changes
4. Effect of snowmelt

C. Ground surface indications of subsurface water
1. Springs
2. Seeps and damp areas
3. Vegetation differences

D. Effect of human activity on groundwater
1. Groundwater utilization
2. Groundwater flow restriction
3. Impoundment and additions to groundwater
4. Changes in ground cover and infiltration opportunity
5. Surface water changes

E. Groundwater chemistry
1. Dissolved salts and gases
2. Changes in radioactive gases

IV. Weather

A. Precipitation
1. Form (rain or snow)
2. Hourly rates
3. Daily rates
4. Monthly rates
5. Annual rates

B. Temperature
1. Hourly and daily means
2. Hourly and daily extremes
3. Cumulative degree-day deficit (freezing index)
4. Sudden thaws

C. Barometric changes

V. Vibration

A. Seismicity
1. Seismic events
2. Microseismic intensity
3. Microseismic changes

B. Human induced
1. Transport
2. Blasting
3. Heavy machinery

VI. History of slope changes

A. Natural process
1. Long-term geologic changes
2. Erosion
3. Evidence of past movement
4. Submergence and emergence

B. Human activity
1. Cutting
2. Filling
3. Changes in surface water
4. Changes in groundwater
5. Changes in vegetation cover, clearing, excavation, cultivation, and paving
6. Flooding and sudden drawdown of reservoirs

C. Rate of movement
1. Visual accounts
2. Evidence in vegetation
3. Evidence in topography
4. Photographs (see Chapter 3)
a. Oblique
b. Aerial
c. Stereoptical data (photographic)
d. Spectral changes
5. Instrumental data (see Chapter 5)
a. Vertical changes, time history
b. Horizontal changes, time history
c. Internal strains and tilt, including time history

D. Correlations of movements
1. Groundwater–correlate with groundwater (III)
2. Weather–correlate with weather (IV)
3. Vibration–correlate with vibration (V)
4. Human activity–correlate with human-induced vibration (VB)

The techniques for obtaining the data will be discussed at greater length later in this chapter. The extent to which any one feature requires evaluation is difficult to determine in advance. Whether any more data are needed will depend on the amount of information already available. However, the process is seldom completed; instead, the work stops when time, money, and patience commensurate with risks and potential costs have been exhausted.

Topography

The topography or geometry of the ground surface is an overt clue to past landslide activity and potential instability. More detail than that shown on existing topographic or project design maps is usually required for landslide studies. Moreover, interpretations made by topographers who are not specifically looking for landslide features can obscure the special geometric or topographic forms that are diagnostic of landslides. Therefore, special mapping is usually necessary. Because the topography of a landslide is continually changing, the area must be mapped at several different times: (a) several years before construction (if data are available), (b) at the time a specific landslide investigation is initiated, (c) at appropriate intervals during the progress of the investigation, and (d) after remedial measures are undertaken. Ultimately, the effectiveness of corrective measures is expressed by whether the topography changes.

Because of the long time span involved, the location of the area should be referenced with some standard location system. Latitude and longitude may be sufficient for studies in remote areas or studies encompassing large sites. State survey coordinate systems and road stationing outside the area of study can provide an effective frame for location. In addition, nearby prominent topographic features should be referenced because man-made features often change and those who must use the data referenced to them may not be aware of those changes.

Geology

The geometry of the subsurface is the most important single factor in the analysis of a landslide. First, the various soil and rock units must be identified. Although it is desirable to associate the geologic units with the named geo-

logic formations that have been defined or previously studied in the area, this activity frequently dissipates more time and effort than are relevant to the evaluation of the landslide. Because the name of a formation seldom reflects its engineering behavior, determining the structural, lithologic, and engineering properties of the formation is far more important than determining its exact age and identification. However, names do have value in comparing landslide activity in one area with that in another that includes the same formations, and relative age can help in describing structural features.

Geologic structure is frequently a major factor in landslides. Although this includes the major large-scale structural features such as folds and faults to which most importance is attached in regional geologic studies, the minor structural details, including joints, small faults, and local shear zones, may be even more important. Changes in the geologic conditions with location give important clues to areas of distress and to potential landslide activity. Offsets in strata, changes in joint orientation, and abrupt changes in dips and strikes are indicators of nonuniform geologic conditions. These must be identified both within the area of potential or observed movement and far enough beyond that area to predict the effect of any planned construction surrounding the landslide zone.

Water

Water is a major factor in most landslides. Concentrations of surface water from rainfall runoff, seeps, and springs are overt indications of topographic changes in landslide-prone areas. For example, unusually deep erosion gullies sometimes suggest that soils and rocks have been weakened by landslide activity. Moreover, surface water entering cracks and fissures caused by earth movement aggravates instability.

Seeps and springs that serve as groundwater exits are another dimension of the water problem. Sometimes, however, too much attention is paid to the exit and not enough to the source. If there is a groundwater exit, there also must be a path of seepage leading to it; thus, the exit of groundwater is a clue to internal water pressures elsewhere. Unfortunately, the layperson sometimes considers seeps and springs to be the cause of earth movements. Seeps uphill from the slide serve as a source of surface water that can infiltrate back into the soil within the slide, thus contributing to instability. However, within the slide zone and downhill from it, the opposite is usually true. Less pressure builds up when water is seeping out of the ground than when the exits for groundwater are blocked. For example, in one major slide area, landslide activity was always preceded by a stoppage of spring discharge near the slide toe; the cessation of movement was marked by an increase in spring discharge.

The various joints, fissures, and more pervious strata that conduct water underground must be identified. These features constitute a part of the subsurface geometry that is not always reflected by the strike and dip of the formations. Even the most insignificant water-bearing stratum can sometimes be the source of trouble and is too often overlooked in favor of the more obvious, but perhaps less dangerous, aquifers. Within each water-bearing formation or fissure is a definite (but changing) groundwater pressure or piezometric level. The groundwater is sometimes perched, leaving the overlying and underlying strata only partially saturated. The formation or fissure can be carrying water under sufficient confined pressure to cause significant reduction in effective stresses within the soil or rock between blocks of impervious materials separated by fissures. To the geologist interested in rock formations and to the geotechnical engineer interested in soil samples, groundwater aquifer identification and piezometric pressure studies are often considered to be of secondary interest, but, in many cases, they constitute the most valuable data gained in the investigation.

Physical Properties

Evaluating the stability of a zone of questionable movement or determining the effectiveness of various corrective measures requires a knowledge of the physical properties of the soil and rock strata. The required data include the properties of both the intact formation and the formation after it has been subject to water pressure changes and to large strains.

The physical properties can be determined in three ways. The conventional approach, which is to test undisturbed samples in the laboratory, has the advantage that stresses and water pressures can be controlled to simulate future environmental changes produced by the anticipated construction and climate variations. However, the process of sampling, transportation to the laboratory, and preparation for testing causes definite changes in the character of the soil and rock before their laboratory testing. A second approach, which is to test the soil and rock in place in the ground, minimizes the disturbing effects of sampling. However, the range in environmental changes that can be induced in the field is severely limited. A third approach is to use indirect tests that measure some physical property related to the engineering parameters involved in the landslide. For example, the compression-wave velocity in a formation, as determined by a seismic refraction geophysical investigation, is related to the joint spacing, density, and rigidity of the soils and rocks through which the wave passes. A formation exhibiting a low compression-wave velocity is generally weaker and less rigid than one exhibiting a high velocity. Unfortunately, the indirect tests require subjective interpretation; therefore, their use in measuring the physical properties of the materials involved is limited by the experience and imagination of the interpreter.

Ecological Factors

A landslide, even one that occurred in the geologic past, has a distinct influence on life systems in the surrounding area. For example, a landslide in a steep, fractured rock mass can produce a loose, jumbled mass of colluvium that is more easily saturated by rain and therefore supports a more luxuriant growth of vegetation than does the undisturbed slope. Thus, the ecosystem of an area can provide a subtle hint of landslide activity. Conversely, the ecosystem effects changes in landslides. For example, deep masses of roots can provide sufficient reinforcement to distort the geometry of the failing soil mass; trees with deep tap roots may even curtail severe movement. A thick

cover of vegetation minimizes rainwash and provides more uniform infiltration of moisture. In contrast, concentrated gullying occurs when an area has been exposed by excavation or when vegetation has been destroyed by fire. Therefore, the ecosystem, and particularly the vegetation within the landslide area, should be compared to that within the surrounding area. Since life systems are changing, a single study at a particular time may not be sufficient; continuing studies during an extended period usually are necessary in order to define the significance of the interrelation between the earth movements and the ecology of an area.

PLANNING INVESTIGATIONS

Area of Investigation

The area of an investigation is controlled by the size of the project and by the extent of the topographic and geologic features that are to be involved in the landslide activity. At sites where there is potential for movement that has not yet developed, the area that must be investigated cannot be easily defined in advance. The extent of the investigation can be better defined once a landslide has occurred. However, in either case, the area studied must be considerably larger than that comprising the suspected activity or known movement for two reasons: (a) The landslide or potential landslide must be referenced to the stable area surrounding it, and (b) most landslides enlarge with passage of time (moreover, many landslides are much larger than first suspected from the obvious overt indications of activity). As a crude rule of thumb, the area studied should be two to three times wider and longer than the area suspected. In some mountainous areas, it is necessary to investigate to the top of the slope or to some major change in lithology or slope angle. The lateral area must encompass sources of groundwater and geologic structures that are aligned with the area of instability.

The depth of the investigation is even more difficult to define in advance. Borings or other direct techniques should extend deep enough to identify those materials that have not been subject to past movement, but that could be involved in future movement, and the underlying formations that are likely to remain stable. The boring depth is sometimes revised hourly as field operations proceed. When instrumentation of a landslide yields data on the present depth of activity, planned depths are sometimes found to be insufficient and increases are necessary. The specifications should be flexible enough to allow additional depth of investigation when the data obtained suggest deeper movements. Longitudinal cross sections should be drawn through the center of the slide and depict possible toe bulges and uphill scarps; circular or elliptical failure surfaces sketched through these limits can suggest the maximum depth of movement. Continuous thick hard strata within the slope can limit the depth. However, at least one boring should extend far below the suspected depth of shear; sometimes deep slow movements are masked by the greater activity at shallower depths. For a second estimate, the depth of movement below the ground surface at the center of the slide is seldom greater than the width of the zone of surface motion.

Time Span

Since most landslides are influenced by climatic changes, a minimum period for investigation should include one seasonal cycle of weather—1 year in most parts of the world. However, because long-term climatic cycles that occur every 11 or 22 years are superimposed on the yearly changes, a landslide investigation could be necessary for more than 2 decades. Such a long investigation is almost impossible, however, because of the need to draw conclusions and take corrective action. Investigations made during a period in which the climatic conditions are less severe than the maximum will prove too optimistic, and those made during a period of bad climate may appear too pessimistic. The worst climatic conditions that develop during the life of the project control the risk to engineering construction. Experience has indicated that many false conclusions have been reached regarding the causes of landslides and the effectiveness of corrective measures because worsened climatic changes were not considered by the engineers and geologists concerned.

Stages of Investigation

An investigation of landslides is a continuing process but, from the practical point of view, may be divided into four stages.

1. The first stage is a preliminary investigation or reconnaissance in which a general overall view of the problem area is gained. The work begins with a review of the published geology in the area and accounts of past land instability. The field study is largely visual and the interpretation is highly subjective. The results of this preliminary evaluation are used as a guide in planning the more intensive, specific investigation during which the major part of the quantitative data are obtained.
2. The second stage, which is more intensive and detailed, includes boring, sampling, trenching, and other specific techniques designed to obtain the data needed to satisfy the objectives outlined in the above checklist. Because of climatic changes, the intensive investigation is preferably undertaken during the season that is least favorable for stability. For example, borings to determine the minimum soil strength or groundwater studies to determine maximum water pressures should be made during periods of snowmelt or following heavy rainfall. A similar investigation made during the driest and hottest period of the year could give completely misleading data.
3. The third stage is iterative. As new data are obtained, they will point to the need for additional data from specific locations. The investigative plan must provide for additional work that was not a part of the initial scope. Experience indicates that the additional work stemming from information obtained during the planned study will range from 30 to 50 percent more than that which was originally considered adequate for the intensive investigation.
4. The fourth stage involves continuing surveillance of any area where activity is suspected or where corrective action has been taken. The surveillance period is indeterminate but should extend through at least one cycle of annual climatic change and, to be most meaningful, should be longer term to include the worst climatic conditions. For example,

corrective work may be done during a number of consecutively dry years, and the area may not be subjected to its worst climatic test until 4 or 5 years later (assuming an 11-year cycle of climatic change). If the climatic changes occur in a 22-year cycle, the period of observation required could be correspondingly much longer. Rarely do those who finance such long-term surveillance have the wisdom and foresight to continue the data gathering, because the period required extends beyond the tenure of most public officials or private managers. However, public and professional interests are best served if surveillance is maintained long enough for the occurrence of the full range of environmental conditions that can reasonably be expected; otherwise, the extent of continuing risk may never be adequately defined.

SITE TOPOGRAPHY

As previously stated, the site topography (surface geometry) is the first clue to potential instability and the degree to which an area has undergone landslide activity. The topography is first determined by aerial surveys (photogrammetry), which provide an overall view of the site conditions. However, because of the detail required and the masking of the vegetation and the landslide itself, detailed ground surveys must be included as a major tool in landslide investigation.

Aerial Survey

Existing Sources of Photography

All of the United States and most of the remainder of the world have been covered by some form of aerial photography or remote sensing, including LANDSAT; the principal sources are given in Chapter 3. Generally, these existing photographs have been made at moderately high altitudes (typically at a scale of 1:10 000 to 1:40 000). Probably the most widely used scales of photography by these agencies are 1:20 000 (1 cm = 200 m; 1 in = 1667 ft) or 1: 24 000 (1 cm = 240 m; 1 in = 2000 ft). At this scale, most landslides appear as minor topographic anomalies and their detailed features, such as scarps, toe bulges, and seeps, can seldom be identified, even from enlargements. However, these photographs are useful in identifying areas that may be prone to landsliding because they may show the typical undulating disturbed topography or arcuate scarps that are associated with past landslides. Such existing photography is frequently a good starting place for evaluating the surface geometry of the site, but it is seldom of sufficient accuracy to provide useful data for detailed landslide studies.

Smaller scale photography can be obtained by the more sophisticated remote-sensing systems of high-altitude photography (1:60 000 and 1:120 000) provided by the National Aeronautics and Space Administration. Although the imagery obtained from LANDSAT with a resolution of 56 x 79 m (185 x 260 ft) is not sufficient to identify the topography of most landslides, it does provide clues to the major geologic structures that sometimes influence landslide activity. However, such high-altitude, small-scale data should be considered as supplementary information that provides clues of regional significance rather than as the primary source of topographic data on landslide-prone areas. One distinct advantage of existing photographic and remote-sensing imagery is that it provides information on ground surface conditions before the particular site becomes of interest for construction. Some aerial photographs of the U.S. Department of Agriculture date from the late 1930s, and imagery of LANDSAT and the Earth Resources Technology satellite dates from the early 1970s.

Color and Color Infrared Photography

For mapping purposes, black-and-white panchromatic photography generally provides the best detail at the lowest cost. However, in the study of landslides, certain features become more obvious in color (*4.15*). Color photography emphasizes differences in vegetation and wet areas through changes in soil color and vegetation vigor. Stratification in exposed soil and rock is often more easily recognized and mapped in color. Color infrared photography is particularly helpful because of two properties. First, most water appears blue in such photography; seeps issuing from bare ground frequently will have a blueish tinge that is far more obvious in the color infrared photography than in either black-and-white or color photography. Second, color infrared photography is useful in mapping hidden cracks and fissures through their influence on growth of vegetation. Fissures above the water table act as drains; the color or image depicts dull red colors of inhibited growth, and springs and sheared zones that hold water sometimes feature more vigorous growth by brilliant reds. However, such inferences should be verified on the ground before they are included on maps.

Thermal Sensing

Thermal sensing involves scanning the ground with a detector that is sensitive to selected portions of infrared radiation. The image produced by the shorter wave (2 to 5 μm) is comparable to the image produced by black-and-white or color infrared photography. In the second range (approximately 8 to 14 μm), the radiation is comparable to the heat radiated from the ground. Thus, for any given texture of ground surface, the level of radiation measured is proportional to the ground temperature. This range of thermal sensing is highly sensitive to small differences in ground temperature. For example, if the imagery is obtained during winter, seeps and springs issuing from the warmer, deep ground will be depicted as warm points contrasting with the cold ground; similar imagery obtained during summer nights will show the seeps and springs as colder than the surrounding ground surface. To be most effective, this sensing must be done during the night or early dawn when there is insignificant infrared reflectance from the sun.

Because of changing angles associated with aircraft movement, the thermal infrared image is seldom a scale representation of the ground feature. Instead, it must be used in conjunction with aerial photographs or accurate maps so that the distorted geometry of the infrared image can be related to the actual geometry of the ground surface and the points depicted on the imagery can be located exactly. The resolution of the imagery is not great because the sensing generally encompasses 0.002 to 0.005 rad (0.115° to 0.286°) of angle from the aircraft or 2 to 5-m (7 to 16-ft)

resolution for 1000-m (3300-ft) height. At high altitude, the heat radiation from significant areas is averaged and small features cannot be detected. Therefore, for locating seeps, springs, small water courses, and other features of particular significance in landslide investigation, the thermal infrared imagery must be flown at low levels, generally 300 to 1000 m (980 to 3300 ft) above the ground surface. In hilly country, this presents problems for aircraft navigation.

In planning for thermal infrared imagery, one must be sure that the exact needs or objectives of the work are transmitted to those who obtain the imagery so that the proper altitudes and sensing range can be selected. Thermal infrared imagery detects temperature differences as small as 1°C (1.8°F), and those differences, in turn, reflect variations in soil moisture and ground heat storage.

Use of Aerial Survey Data

Aerial survey data are used in two ways. First, and most important, when used in coordination with ground surveys (including reference points established on the ground surface), they provide detailed topographic maps of the area through photogrammetric processes. This is the procedure with which organizations obtaining aerial survey data are most familiar and that requires the least guidance. A second use of aerial photography and remote-sensing data is in interpretation or terrain evaluation (described in Chapter 3). Because the technical quality of photographs and imagery for accurate mapping is more demanding, the specifications for photography should be directed by topographic requirements. However, the special needs for interpretation should also be considered so that one photographic mission can serve both purposes.

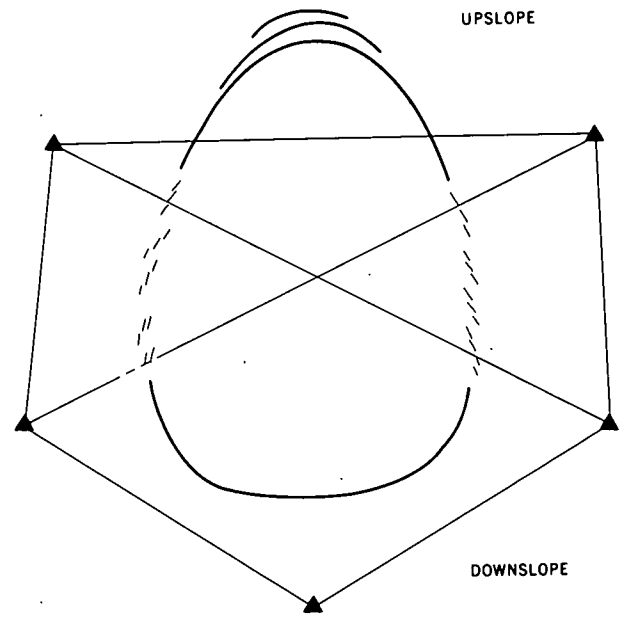
Terrestrial Photogrammetry

Photogrammetric measurements of ground geometry can be made from oblique photographs obtained at the ground surface. For example, two or more permanent photographic sites that overlook a slide area can be used to monitor slide movement by successive sets of simultaneous photographs. Such observations have been used to measure changing dam deflections. Although the data reduction is more complex than that for photogrammetric mapping, the technique is useful for determining movement of any selected points, provided they can be seen in the photograph.

Specifying Scale and Coverage Quality

The scale of photography and thermal imagery must be determined on the basis of the size of the features to be identified. In the mapping of springs, seeps, and fissures, a resolution circle 0.5 to 1 m (1.5 to 3 ft) in diameter is desirable. A suitable scale for the aerial photography for landslide studies is of the same order that is required for final highway alignment studies (from 1:3000 to 1:6000 on contact prints). Maps are drawn to a scale of 1:1000 (1 cm = 10 m; 1 in = 83 ft) to 1:5000 (1 cm = 50 m; 1 in = 417 ft) and with contour intervals of 0.5 m (1 to 2 ft) for most slides. Good quality aerial photographs for mapping and interpretation are necessary tools at the beginning of an investigation, but additional coverage is desirable after episodes of

Figure 4.1. Bench marks and triangulation leveling network.



enhanced movement. Thermal imagery is useful after periods of unusually dry or wet weather. However, the various forms of thermal imagery are most revealing when the ground surface can be observed (that is, when deciduous vegetation is free from leaves). Aerial photographs taken at intervals for several years after corrective measures are taken provide an excellent tool for assessing the overall benefits achieved by the measures and for obtaining a preliminary view of the effect of the landslide and associated corrective measures on the ecosystem of the area. Since satisfying all those needs is not always possible, it may not be feasible to bring all of the tools of aerial photography and remote sensing into play in any single investigation.

Ground Surveys

On-the-ground surveys are necessary to (a) establish the ground control for photogrammetric mapping and instrumentation, (b) obtain topographic details where the ground surface is obscured by vegetation (this is particularly important because of the accuracy required in mapping landslides), and (c) establish a frame of reference against which movements of the ground surface can be compared.

Ground Control for Instrumentation

The first requirement is a system of local bench marks that will remain stable during the course of the investigation and as far into the future as movements will be observed. These must be located far enough outside the suspected zone of sliding that they will not be affected by any movements. Ultimately, the bench marks should be referenced to control monuments of federal and state survey systems. However, for convenience, a subsystem of local bench marks should be established close enough to the zone of movement that they can be used as ready references for continuing surveys. At least two monuments of position and elevation should be established on each side of the zone of sliding or sus-

pected movement; as indicated in Figure 4.1, these should be as close as possible to the movement zone, but not influenced by future enlargement of the slide. Experience suggests that the distance from a bench mark to the closest point of known movement should be at least 25 percent of the width of the slide zone. In areas of previous landslides, the minimum distance may be greater. In mountainous areas, adequate outcrops of bedrock can sometimes be found uphill or downhill from the landslide; in areas of thick soil, deep-seated bench marks may be necessary.

Control Network

The bench marks should be tied together by triangulation and precise leveling loops. If there are enough bench marks, the movement of any one can be detected by changes in the control network. Intermediate or temporary bench marks are sometimes established closer to the zone of movement for use in the more frequent surveys of the landslide area. However, these should be checked against the permanent monument grid each time they are used.

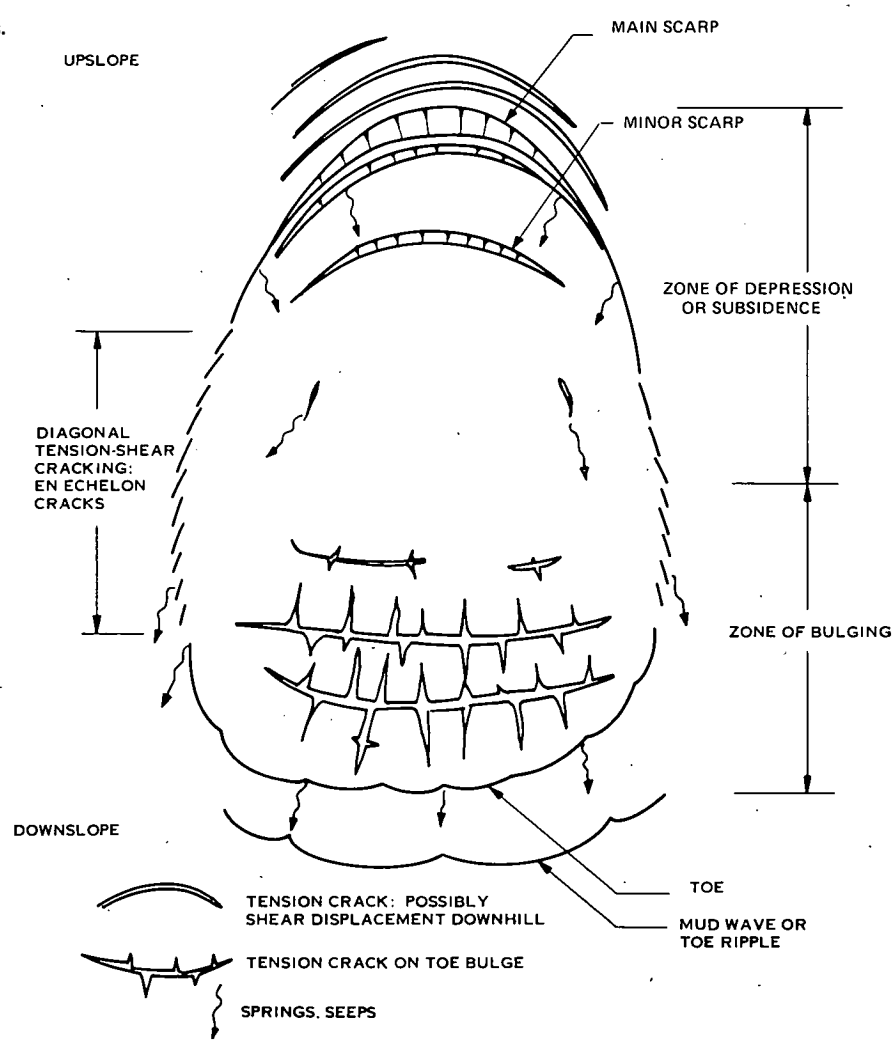
Topography

As previously stated, topography obtained from aerial photography may not be sufficiently accurate or detailed for landslide studies because vegetation obscures the ground surface. Therefore, detailed on-site mapping is necessary. Major features, such as scarps, bulges, and areas of jumbled topography, should be defined (Figure 4.2). Because of the changing nature of landslides, the surface surveys should be conducted at the same time the photography is taken; otherwise, the movements of the landslide will confuse the topographic map. Even then, it may not be possible to obtain a precise correlation between the surface topography determined on the ground over a period of days or weeks and that obtained at a single instant from aerial surveys. Differences should be expected, and these should be noted on the topographic maps that are produced.

Cracks, Seeps, and Bulges

Although many cracks, seeps, and bulges, as well as other minor topographic details, can be identified in aerial photography, their full extent can seldom be determined unless the photographs are taken with an unusually high degree of resolution in vegetation-free areas. Therefore, independent crack and bulge surveys should be made by surface methods. Developing cracks are often obscured by grass, leaves, and root mats, particularly at their ends; these cracks should be

Figure 4.2. Cracks, bulges, scarps, and springs.



carefully uncovered so their total extent can be mapped. Hidden cracks can be identified by subtle changes in leaf mold patterns, tearing of shrubs, and distortion of trees and tree root systems. Boulder alignments or sliding trajectories should also be noted. Cracks should be staked on both sides, as well as referenced to the movement system, because the entire crack system shifts with continuing landslide movement.

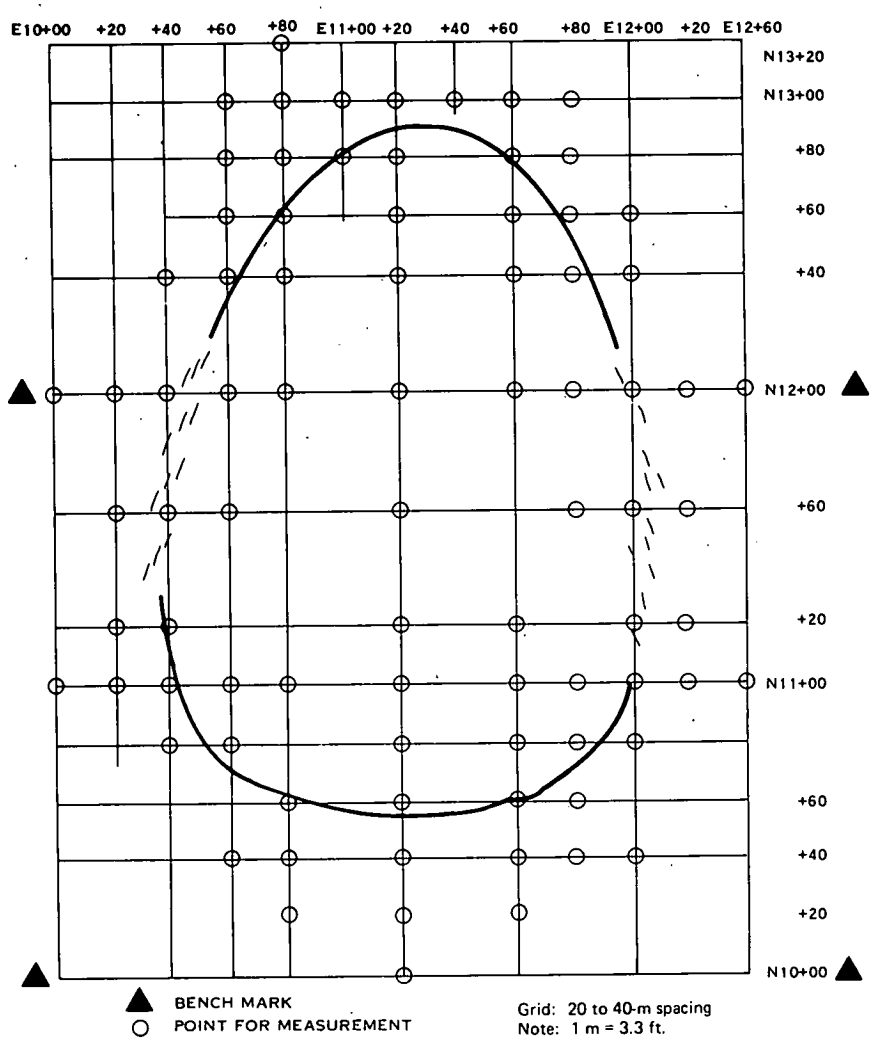
Seeps and springs are the ultimate exits for water-bearing strata and cracks and thus are clues to the water paths that influence soil and rock stability. Because seeps often follow cracks that have been opened by soil or rock movement, they can sometimes be traced to sources uphill. The points of disappearance of surface runoff into cracks and fissures should also be mapped. Seeps, springs, and points of water loss change with rainfall, snowmelt, and ground movement. Thus, meaningful data on their location and shifts cannot be obtained by a single survey or regular intervals of observation. Instead, they should be located during and shortly after periods of intense rainfall or snowmelt and after episodes of significant movement.

Movement Grids and Traverses

The continuing movement of a landslide can be measured by a system of traverses or grids across the landslide area (Figures 4.3 and 4.4). Typically, a series of lines more or less perpendicular to the axis of the landslide, spaced 15 to 30 m (50 to 100 ft) apart with stakes at intervals of 15 to 30 m (50 to 100 ft), should be maintained and referenced to the control bench marks. Grids should be laid out so that the reference points are aligned with trajectories of maximum slope or apparent movement if sliding is continuing. In addition, where soil and rock weaknesses cause secondary movements that are skewed to the major slide, intermediate points should be established. For small slides or widely spaced areas of suspected movements, single traverse lines of reference (Figure 4.4) are often used.

Appropriate reference wands or flags should be placed nearby so that the staked points can be found despite severe movement. The elevation and coordinates of each point on the traverse or reference grids should be determined by periodic surveys. In areas where highly irregular topography suggests rapid differences in movement from one point to another, reference points should be spaced more closely, regardless of any predetermined grid pattern. Such closely spaced stakes help to define the lateral limits of the landslide, as well as the direction of movement of localized tongues within the slide. This is particularly important in the later stages of movement if secondary flows develop

Figure 4.3. Observation grid.



from the weakening of the soil by sliding. Depending on the rate of movement, these grid points should be checked at intervals ranging from a few days to several months. In addition, they should be observed after periods of unusual weather changes, such as snowmelt, high rainfall, or sharp temperature changes. In this way, any relation between landslide movement and climatic changes can be established.

Crack Measurement

Most earth movements are accompanied by cracking of the ground (Figure 4.2). The principal scarp is most prominent; it is paralleled by developing scarps (arc- or crescent-shaped cracks with the points of the crescents pointing downhill from the scarps) and secondary or older scarps downhill. Along the lateral limits of the slide, cracks are formed by differential shear between the moving mass and the intact soil beyond. The shear often generates parallel diagonal tension cracks (termed en echelon) in this zone. In the bulge zone near the toe of the slide, there are frequently short tension cracks parallel to the direction of movement as well as crescent-shaped tension cracks with the points of the crescents pointing uphill. If the movement extends below the toe of the slope, there will be bulge and shear cracks or subtle ripples in the soil well beyond the slide toe. Survey points should be set on the more prominent of these features and beyond them, provided they are not close to the grid or traverse points.

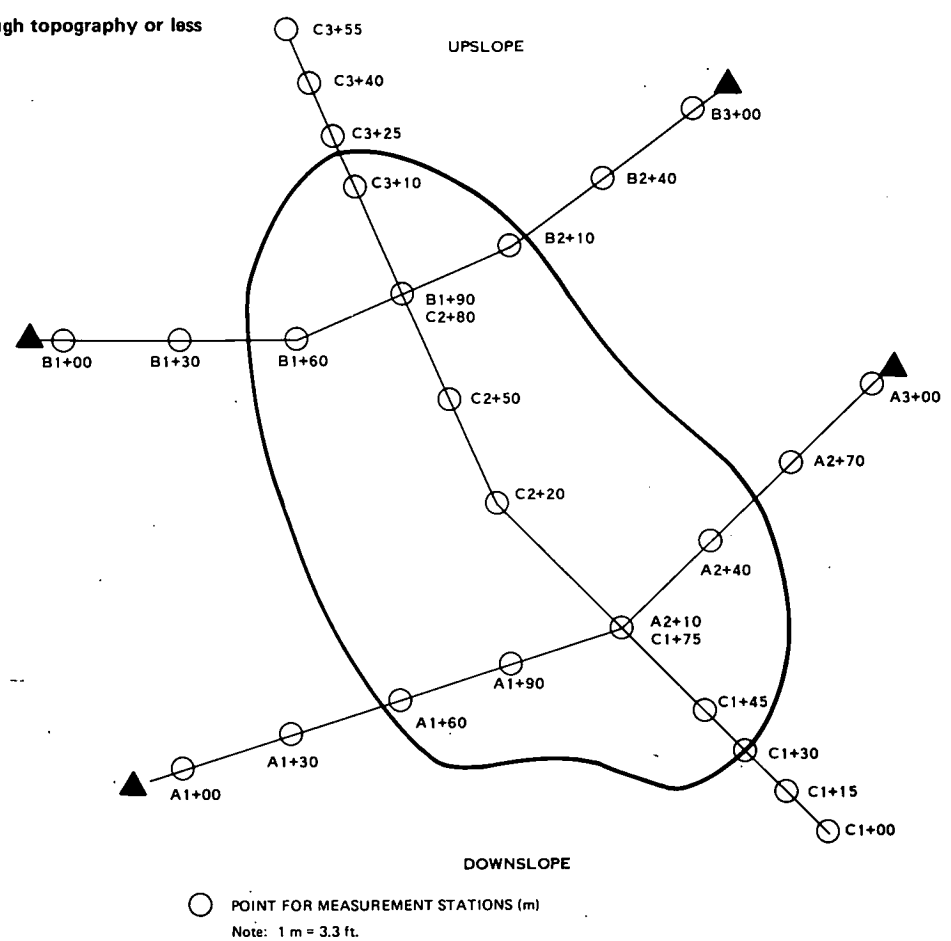
Instrumentation of landslides is discussed in detail in Chapter 5; however, certain supplementary measurements should be a part of the survey program. For example, crack width changes should be measured directly by taping across stakes set on each side of the crack; vertical offsets on cracks and scarps should be obtained by direct measurement. These direct measurements serve as a check to the more sophisticated systems (discussed in Chapter 5) that determine the in-depth movements. In addition, the surface location and elevations of reference points of the instrumentation systems must be determined at each time of observation.

Representation of Topographic Data

The photogrammetric data are correlated with the ground survey controls and detailed topography, and they are used to establish two or more maps of the landslide area. The first encompasses the landslide (or suspected landslide) plus the surrounding area; the topography extends uphill and downhill beyond major changes in slope or lithology. Topography should be developed on each side for a distance of approximately twice the width of the sliding area (or more when the zone of potential movement is not well defined). Typical scales for such mapping of large slides may be 1:2500 to 1:5000 (1 cm = 25 m to 1 cm = 50 m; 1 in = 208 ft to 1 in = 417 ft).

The second topographic map is more detailed and encom-

Figure 4.4. Observation traverses for rough topography or less important landslides.



passes the observed slide area plus all of the uphill and downhill cracks and seeps associated with the slide. Typically, the detailed map extends beyond the landslide uphill and downhill for a distance of half the length of the slide or to significantly flatter slopes. Horizontally, the detailed topography should extend at least half of the width of the slide area beyond the limits of the slide. Contour intervals in such detailed topography should be as close as 0.5 m (1 to 2 ft). The horizontal scale is typically 1:1000 (1 cm = 10 m; 1 in = 83 ft) or larger.

Profiles

In addition to the topographic map, profiles of the slide area are prepared (Figures 4.5 and 4.6). The most useful of these follow the lines of steepest slope of the slide area. Where the movement definitely is not in the direction of the steepest slope, two sets of profiles are necessary: One set should be parallel to the direction of movement and the other parallel to the steepest ground surface slopes. In small landslides, three profiles may be sufficient; these should be at the center and quarter points of the slide width (or somewhat closer to the edge of the slide than the quarter points). For very large slides, the longitudinal profiles should be obtained at spacings of 30 to 60 m (100 to 200 ft). It is particularly important that the profiles be selected so as to depict the worst and less critical combinations of slope and movement within the landslide area. To have at least one additional profile in the stable ground 15 to 30 m (50 to 100 ft) beyond the limits of the slide area on each side of the slide is usually desirable so that the effect on the movement of ground surface slope alone can be determined.

Each longitudinal profile of the landslide is generally plotted separately. If there are significant movements, the successive sets of elevations and consecutive profiles can be shown on the same drawing to illustrate the changing site topography. The original topography should be estimated from old maps and shown for comparison, where possible. However, to reference old maps precisely to the more detailed topography obtained for the landslide investigation is difficult. Differences between existing topography and preslide topography may represent survey mismatches as well as actual changes in the ground surface. Adjustments of the preslide profile from old maps to the profile from new surveys can be made by comparing old and new topography beyond the limits of observed slide movements.

Displacement Vectors and Trajectories

The survey grids and other critical points are entered on the

Figure 4.5. Landslide contours and profile location.

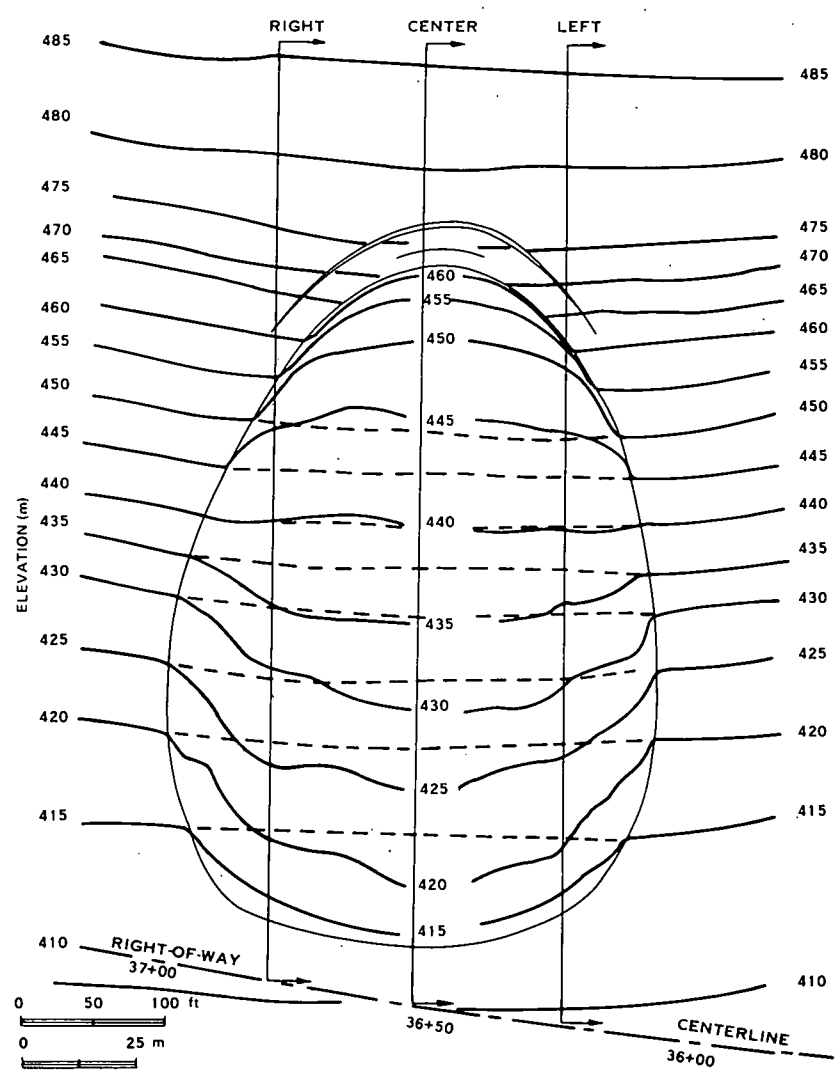
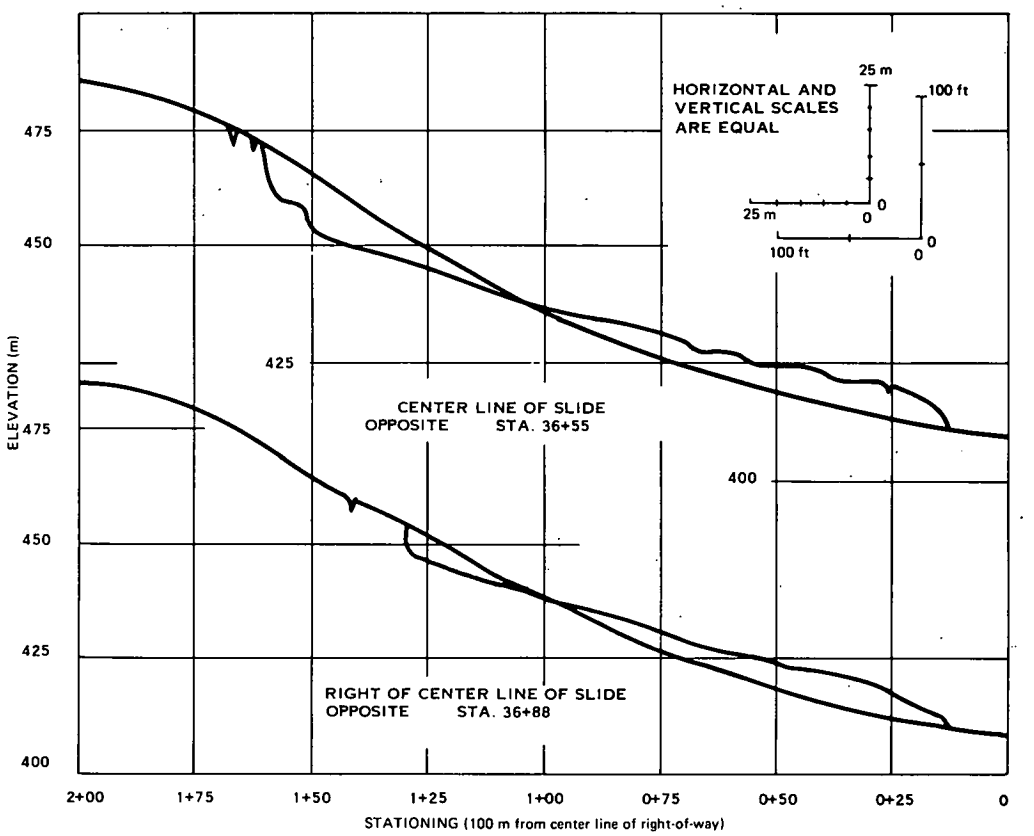


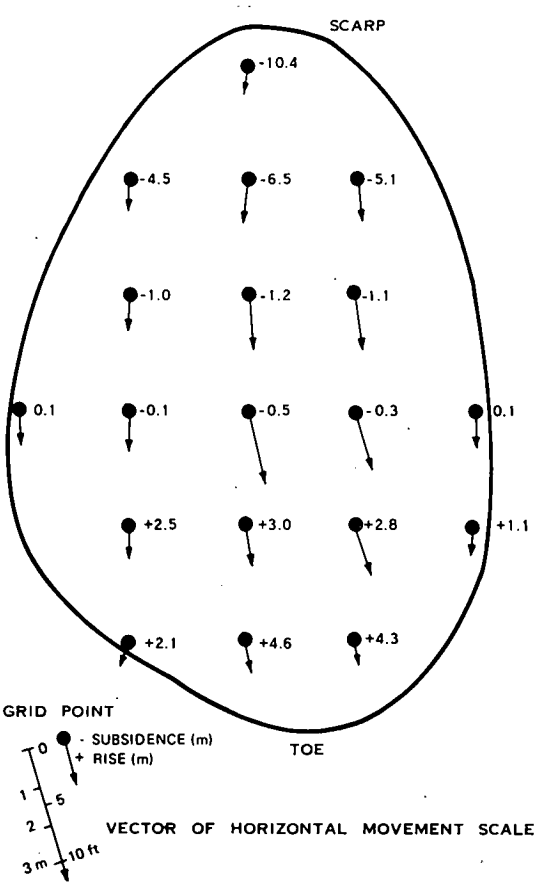
Figure 4.6. Landslide ground surface profiles.



more detailed topographic map of the landslide area. Both the topography and the depicted grid points should be referenced to the same data. From the consecutive readings on the survey grids and traverses, the horizontal and vertical displacements of the ground surface can be determined. If the movements are large, the subsequent positions of the reference points can be plotted on the topographic map. However, if the movements are small, the successive positions of the stakes may be plotted separately to a larger scale depicting vectors of movement. The vector map depicts only the slide outlines, reference points, and vectorial movements (Figure 4.7). Although the initial positions of the points are shown in their proper scale relations, the vectors of movement are plotted to a larger scale; this difference in scale should be noted. Elevations at successive dates can be entered beside the grid points.

Because the topography changes significantly with the continuing movement, the dates of the surveys should be noted on the maps. Furthermore, if there is a significant period of time between the dates of the surveys that establish the topography and the surveys that establish the movement grid, the elevations of the points on the grids will not necessarily correspond to those on the topographic map.

Figure 4.7. Movement vectors since beginning of measurement.



SUBSURFACE EXPLORATION

Geologic Reconnaissance

A thorough knowledge of the geology of the area is necessary to identify landslide-prone zones as well as to analyze and correct existing slides. The importance of recognizing

structure, groundwater, and weathering in the prevention and evaluation of sliding has been emphasized by Philbrick and Cleaves (*4.9*), Záruba and Mencl (*4.18*), and Deere and Patton (*4.4*). Although data have been published on the major geologic formations and structural features of most of the world, they are seldom in sufficient detail for landslide studies. As long as their extent is comparable to that of the failure zone, small changes in bedding and geologically minor fractures or irregularities in structure, which are seldom shown in published maps and reports, influence failure as significantly as regional features. The local geology is determined by surface observation (geologic reconnaissance) and by interpretation of the subsurface exploration data. The reconnaissance generates an estimate of the local geology and aids in selecting locations and techniques for subsequent exploration and in interpreting the results of the overall investigation.

Outcrops

The principal means for estimating the geology of an area is the outcrop, which is defined as "that part of a geologic formation or structure that appears at the surface of the earth" (*4.1*). Some geologic formations can be identified indirectly by characteristic landforms and others can be deduced from soils that are derived from the weathering of the formation; however, the primary element used in identification is the outcrop itself (rock, residual soil, or even old landslide debris). Outcrops can be examined on steep slopes, in river channels, in highway and railroad cuts, and in quarries and borrow pits. The relation between geologic formations is determined by correlating structure, lithology, and unit thicknesses with site topography. This is a major technique for geologic mapping and is described in texts on field geology (*4.3, 4.7*). However, outcrops can be misleading. The formations may have been displaced or distorted by ancient landslides or by rapid weathering of less-resistant strata. Some formations harden on exposure, especially in regions of highly seasonal rainfall, and give a false impression of the strength or stability of the formation. The outcrop data should be correlated with deep samples before final conclusions are reached.

Faults and Joints

Many geologic discontinuities, such as unconformities, cavities, formation contacts, and facies changes, can affect slope stability. Two of the most prominent, and perhaps most readily identified, are faults and joints. A fault is defined as a surface or zone of rock fracture along which there has been displacement parallel to the surface of the fracture. Joints are rock cracks or partings without displacement parallel to the surface. The recognition of faults and joints is particularly important to predesign and site or route selection. The potential for instability is greater in areas with extensive faulting or close jointing than in areas without discontinuities. Revisions in route or locations of engineering structures may be imperative if the potential is serious; alternatively, the design can be altered to fit the situation.

The strike of the fault, angle of dip of the fault plane, type and competency of the associated rock, extent of the fault (especially the thickness of the sheared or gouge zone), and condition of the rocks and materials on either side of the zone should be determined for both site selection and evaluation of an existing slide. If available, geologic maps may show the location of major faults. If detailed maps are not available, an experienced interpreter can often identify questionable areas from their topographic reflections on maps, aerial photographs, and LANDSAT imagery. These areas are then located in the field to determine their

Figure 4.8. Slide in sandstone overlying shale in Tennessee.

possible significance with regard to site or slide.

Joint systems are seldom indicated on geologic maps, but they are often more troublesome than faults as far as slope stability is concerned. The strike, dip, and spacings of the various joint sets are determined by field mapping of outcrops and a supplementary examination of the rock cores. Statistical depictions of orientation, dip, and spacing or frequency (average number of joints per meter) can be correlated with the slope geometry, proposed cutting and filling, or observed slide features. Close joints in areas involving several rock types may be especially troublesome. In Figure 4.8, for example, sandstone overlies shale. The differences in density, permeability, strength, and rigidity of these materials in the near-vertical slope have caused rock falls. Had the position of these rock types been reversed or had the joints been less frequent, the problem would likely have been less severe. Had the geology of this cut been known in advance, a design could have been formulated to fit joint patterns and thus reduce the maintenance now required. Deere and Patton (*4.4*) have described slopes in interbedded shale and sandstone as one of the most common slide problems.

Inclined Bedding

Bedding or foliation inclined downward toward the slope face is a second major structural factor in instability. The dip and strike can be measured in outcrops; however, in areas of rock folding, there are frequently large local undulations that are far more unfavorable to stability than can be inferred from adjacent outcrops. As with faults, regional directions and angles of dip of the bedding sometimes can be discerned from geologic maps. However, as with faults and joints, the local structure that controls stability must be verified or revised by field study in test pits or by examination of rock cores (see later section on boring and sampling techniques and Table 4.1).

Generally, the preferred route selections should be in areas where the bedding dips into the wall of the excavation. Since this is not always possible, designs can be developed to compensate for the unfavorable bedding. Figure 4.9 shows a typical bedding-plane slide in hard rock (metasiltstone and metasandstone) in which the direction of dip is toward the roadway,

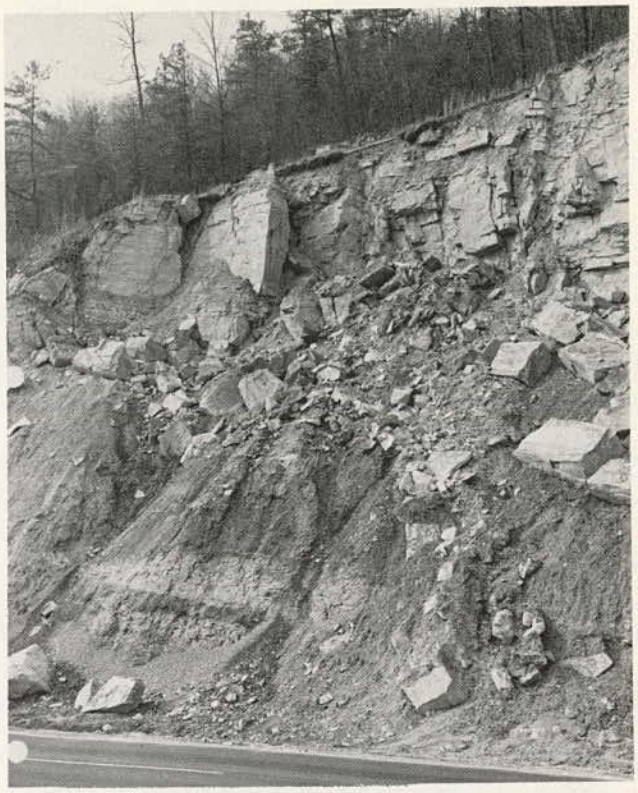
Relict Structure

Residual soils, as a result of the processes by which they were formed, sometimes exhibit the structural characteristics of the geologic formations from which they were derived. This relict structure often influences slope stability in soils in a manner similar to that in which bedding joints and faults influence rock stability. In such cases, the parameters that reflect soil strength, cohesion and angle of friction of the intact soil, may prove misleading. Strength tests should evaluate the surfaces of the relict structure as well as the intact soil; analyses must reflect the orientation of weaknesses defined by the relict structure.

Landforms

The study of landforms is an integral part of the study of

Figure 4.9. Bedding-plane slide in hard metasiltstone and metasandstone in Tennessee.



outcrops and geologic structures. As pointed out in Chapter 3, this study can be done to a great extent with maps and aerial photographs, but to understand all the relations involved requires that the inferences from remote sensing be verified in the field. If the investigation is concerned with sliding that has already occurred, the investigator first reconstructs the conditions at the site prior to sliding. This can be done with the help of maps and aerial photographs. If sliding has not occurred and the investigator is concerned with slide prevention in route or site selection and design, similar landforms and comparable construction in the area should be studied. Failures and successes in areas with similar formations and conditions will help to indicate the behavior of future routes or sites.

Seeps, Springs, and Poorly Drained Areas

Drainage should be noted and mapped in as much detail as possible at the outset of the investigation. Much of this can be done with the aid of large-scale topographic maps and aerial photographs. Localized seeps, poor drainage, and wet-ground indicators, such as cattails and willows, cannot always be seen in photographs; these can be found through careful surface reconnaissance and their locations added to the detailed topographic maps.

Evidence of Past Instability

Many clues can often alert the investigator to past landslides and future risks. Some of these are hummocky ground, bulges, depressions, cracks, bowed and deformed trees, slumps, and changes in vegetation. The large features can

be determined from large-scale maps and aerial photographs; however, the evidence often is either hidden by vegetation or is so subtle and apparently inconsequential that it can only be determined by direct observation. Even then, only one intimately familiar with the soil, geologic materials, and conditions in that particular area can recognize the potential hazards.

Boring, Sampling, and Logging

Boring, sampling, and correlating of the data to develop the three-dimensional subsurface geometry are the most vital parts of the field investigation. The soils and rocks responsible for stability are hidden beneath the ground surface. Although their structure and physical properties can be inferred from the topography and outcrops, quantitative data must be obtained by more direct methods. The right kind of equipment and the capacity to change equipment are essential to a boring and sampling program. Hence, it is necessary for the investigative unit to have access to the appropriate types of drills and tools, tractors, bulldozers, backhoes, and other types of auxiliary machines to gain access to rugged terrain and to make test trenches and pits as needed.

Boring and Sampling Program

The subsurface investigation is only as good as the boring program; the success of the program is measured by the number and quality of samples collected and the reliability of the boring records produced. This phase of the investigation is both an art and a science: It is an art in that it requires a skilled craftsman to advance a boring through complex soil and rock formations aggravated by the distortions that are usually associated with landslides and to consistently collect samples that are representative. It is a science in that those materials and conditions must be properly identified and correlated if the correct interpretations are to be made of their significance. The objectives of the program are

1. Identify the weaker formations that are likely to be involved in movement;
2. Identify the stronger formations that offer significant resistance or that might limit the extent of the zone of movement or provide support for retaining structures;
3. Locate aquifers, define groundwater levels and pressures, and determine water chemistry; and
4. Obtain quantitative data on the physical properties of the formations for use in analyses of stability.

The layout and spacings of the borings depend on the area, configuration, and estimated depth of the slide or, where a suspected or potential slide situation exists, on the geometry of the ground surface. For a suspect area in which sliding has not developed, the boring layout is a grid that includes representative positions up and down the slope and along the length of the slope, as shown in Figure 4.10. Where a slide has occurred, the borings focus on the critical areas of the zone of movement, as well as on adjacent areas that have not yet failed, as shown in Figure 4.11. Philbrick and Cleaves (*4.9*) suggest that a profile of borings be developed along the centerline of the slide; the first boring should be placed between the midpoint and scarp or head of the slide. This profile should coincide with the

Figure 4.10. Grid of borings in suspect area before sliding commences.

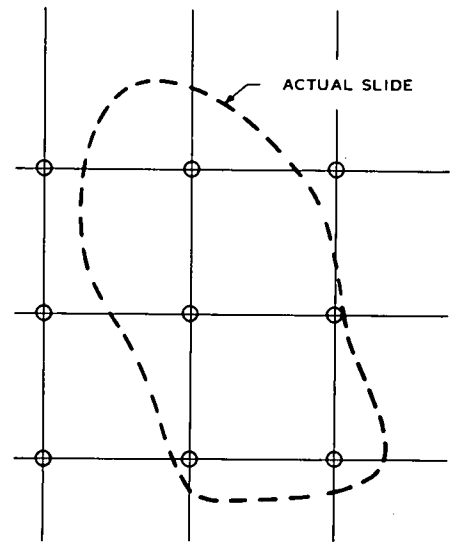
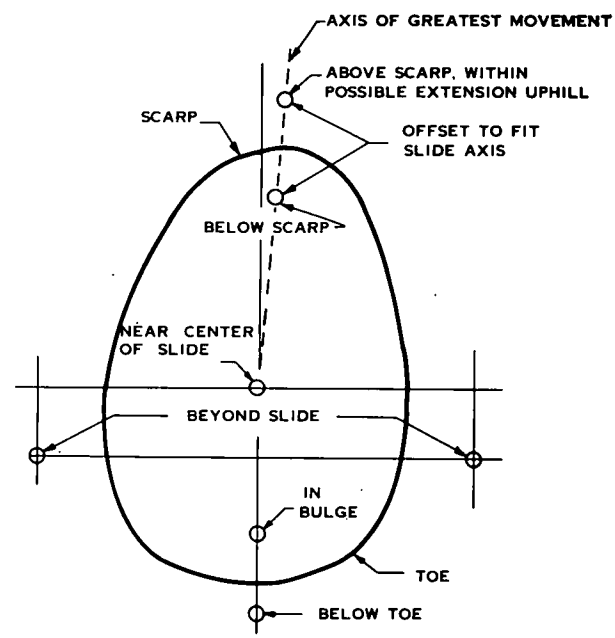


Figure 4.11. Location of borings in slide area (borings are on grid or offset slightly).



topographic profile of maximum slope (see earlier section on ground surveys). The next most important area to be explored, according to Philbrick and Cleaves, is the foot or bulge zone of the slide area. This is the area that usually continues to undergo the most change once sliding has occurred. Such changes are due primarily to the shear surface or zone being progressively softened because of fracture, rainfall infiltration, or blocked groundwater drainage. Moreover, this area is critical in the design of restraining structures that can help minimize continuing movement. Other borings should be distributed throughout the slide. The area outside the slide perimeter should also be drilled and sampled to provide a reference and to enable prediction of the amounts of material that might be involved in future movements.

Boring and Sampling Techniques

The boring and sampling techniques that can be employed are innumerable, and selection depends on the information required, the nature of the soil and rock, the topography and ground trafficability, and the amount of money available. ASTM standards, standards of other associations, books on drilling and sampling, and textbooks on geotechnical engineering (for example, *4.14, 4.16*) describe methods of boring and sampling and their applications and should be consulted for details. Those techniques particularly adapted to landslide studies are summarized in Table 4.1.

The type of sample obtained depends on the information needed. Oriented cores are required to determine the strike of inclined bedding or fractures. Samples from test borings are adequate for identification of formations, but samples from thin-wall tubes or rotary coring are required for good shear and consolidation tests. Accurate and detailed records of the conditions encountered are essential. If samples are lost, a description of the drilling peculiarities may imply the soil and rock condition. When samples are obtained, their value must be assessed from a detailed examination by a geologist or geotechnical engineer, guided by the driller's records. Because the act of sampling changes soils and rocks, the factors involved in those changes must be known to estimate the extent of alteration. Finally, the samples must be carefully preserved, packed, and handled so they will not be unduly changed by exposure and shipping.

Drilling Equipment

One of the problems common to most landslide investigations is accessibility. The same instability that generates movement makes accessibility difficult. For this reason, the investigative unit should be equipped with some type of all-terrain vehicle. Too often, materials and conditions within a particular slide may be underestimated or overlooked simply because of inadequate borings at critical, but inconvenient, inaccessible points. The drilling industry, in collaboration with manufacturers of specialized vehicles, has been able to develop subsurface exploration equipment that is highly versatile and mobile for work in rugged, steep terrain.

Borehole Logging

Because of the extreme variations in the character of the soil and rock and perhaps because of inadequacies on the part of those who perform the boring and sampling and test pit work, there may be gaps in the underground profiles established from any of the borings or geophysical studies. In some instances, the techniques of borehole logging borrowed from the petroleum exploration industry are fruitful. All are based on lowering a sensing device into an open borehole and measuring the soil and rock characteristics at closely spaced intervals of depth. A number of different qualities can be observed, including self-potential of the ground, electrical resistivity within a relatively short vertical distance, nuclear radiation, sound wave or impulse response, density based on nuclear absorption, and water content based on hydrogen ion reaction.

The product of this logging is a graph of each property plotted as a function of depth. The results may have significance in identifying the ion concentration and density of the strata. These aid in identifying soils and rock directly from the boring data. They are particularly useful where there are gaps in the data, such as core loss in broken rock. An even more valuable use of this information lies in establishing the correlation of strata between one boring and another. For example, it is difficult to compare samples obtained from two different holes to determine whether soils or rocks that have similar classification characteristics represent the same stratum. However, by comparing the continuous borehole logs, one can match the patterns of the different properties; similar patterns suggest similar stratification. Thus, while borehole logging may have limited engineering significance by itself in one hole, it is a significant tool for boring interpretation and correlation when used in adjacent holes.

Test Pits and Trenches

One of the best ways to sample and determine the structure and other physical properties of soils and weathered or weak rock foundations is by excavating pits or trenches. Shallow test pits can be excavated with hand tools. Mechanical equipment, such as backhoes, clamshells, draglines, or tractors equipped with front-end loaders, are required for deep pits or long trenches. The sides of the excavation should be sampled, logged, and photographed in detail to provide a three-dimensional picture of the materials and structure. Pits and trenches also provide excellent sites for in situ testing. When the observations and tests are complete, the excavation should be filled or, in some cases, incorporated in the remedial design by serving as a drainage outlet.

Geophysical Studies

Geophysical exploration uses the changes in certain force systems in the earth to define possible boundaries between different materials as well as to estimate some of the engineering properties. The forces include elastic shock waves, gravity, and electric current, none of which is directly concerned in landslide behavior. Thus, the methods are sometimes termed indirect exploration; the data of interest are inferred from the properties measured. Geophysical methods do not replace borings and sampling or test pits and trenches. Rather, they supplement these procedures and greatly reduce the time and cost and the environmental problems that often result from large-scale drilling operations.

Resistivity

Resistivity measurements are made by passing electric current through the ground and measuring the resistance of the various formations to current flow. The current flow is largely electrolytic in that it is dependent on moisture and dissolved salts within the soils and rocks. The Wenner method, which is the simplest and most commonly used, uses four electrodes, spaced equally in a straight line at the ground surface. Current is passed into the ground through the outer two electrodes, and the difference in potential generated by the resistance to current flow is measured between the inner two electrodes. The greater the spacings

Table 4.1. Boring, core drilling, sampling, and other exploratory techniques (*4.2, 4.8, 4.11, 4.14*).

Method and Reference	Procedure	Type of Sample	Applications	Limitations
Auger boring, ASTM D 1452	Dry hole drilled with hand or power auger; samples preferably recovered from auger flutes	Auger cuttings; disturbed, ground up, partially dried from drill heat in hard materials	In soil and soft rock; to identify geologic units and water content above water table	Soil and rock stratification destroyed; sample mixed with water below water table
Test boring, ASTM D 1586 (Figure 4.15)	Hole drilled with auger or rotary drill; at intervals samples taken 36-mm ID and 50-mm OD driven 0.45 m in three 150-mm increments by 64-kg hammer falling 0.76 m; hydrostatic balance of fluid maintained below water level	Intact but partially disturbed (number of hammer blows for second plus third increment of driving is standard penetration resistance or N)	To identify soil or soft rock; to determine water content; in classification tests and crude shear test of sample (N-value a crude index to density of cohesionless soil and undrained shear strength of cohesive soil)	Gaps between samples, 30 to 120 cm; sample too distorted for accurate shear and consolidation tests; sample limited by gravel; N-value subject to variations depending on free fall of hammer
Test boring of large samples	50 to 75-mm ID and 63 to 89-mm OD samplers driven by hammers up to 160 kg	Intact but partially disturbed (number of hammer blows for second plus third increment of driving is penetration resistance)	In gravelly soils	Sample limited by larger gravel
Test boring through hollow-stem auger	Hole advanced by hollow-stem auger; soil sampled below auger as in test boring above	Intact but partially disturbed (number of hammer blows for second plus third increment of driving is standard penetration resistance or N); N-value may be distorted by auger and should be compared with ASTM D 1586	In gravelly soils (not well adapted to harder soils or soft rock)	Sample limited by larger gravel; maintaining hydrostatic balance in hole below water table more difficult
Rotary coring of soil or soft rock	Outer tube with teeth rotated; soil protected and held by stationary inner tube; cuttings flushed upward by drill fluid (Denison—fixed cutter on outer tube; Pitcher—spring-loaded on outer tube; Acker air-mud core barrel—larger clearances for viscous driling fluid)	Relatively undisturbed sample, 50 to 200-mm wide and 0.3 to 1.5 m long in liner tube	In firm to stiff cohesive soils and soft but coherent rock	Sample may twist in soft clays; sampling loose sand below water table difficult; success in gravel seldom occurs
Rotary coring of swelling clay or soft rock	Similar to rotary coring of rock; swelling core retained by third inner plastic liner	Soil cylinder 28.5 to 53.2 mm wide and 600 to 1500 mm long encased in plastic tube	In soils and soft rocks that swell or disintegrate rapidly in air (protected by plastic tube)	Sample smaller; equipment more complex
Rotary coring of rock, ASTM D 2113	Outer tube with diamond bit on lower end rotated to cut annular hole in rock; core protected by stationary inner tube; cuttings flushed upward by drill fluid	Rock cylinder 22 to 100 mm wide and as long as 6 m depending on rock soundness	To obtain continuous core in sound rock (percentage of core recovered for distance drilled depends on fractures, rock variability, equipment, and skill of driller)	Core lost in fracture or variable rock; blockage prevents drilling in badly fractured rock; dip of bedding and joints evident but not strike
Rotary coring of rock, oriented core	Similar to rotary coring of rock above; continuous grooves scribed on rock core with compass direction	Rock cylinder, typically 54 mm wide and 1.5 m long with compass orientation	To determine strike of joints and bedding	Method may not be effective in fractured rock
Rotary coring of rock, wire line	Outer tube with diamond bit on lower end rotated to cut annular hole in rock; core protected by stationary inner tube; cuttings flushed upward by drill fluid; core and stationary inner tube retrieved from outer core barrel by lifting device or "overshot" suspended on thin cable (wire line) through special large diameter drill rods and outer core barrel	Rock cylinder 36.5 to 85 mm wide and 1.5 to 4.6 m long	To recover core better in fractured rock, which has less tendency for caving during core removal; to obtain much faster cycle of core recovery and resumption of drilling in deep holes	Same as ASTM D 2113 but to lesser degree

Table 4.1. Continued.

Method and Reference	Procedure	Type of Sample	Applications	Limitations
Rotary coring of rock, integral sampling method (*4.10*)	22-mm hole drilled for length of proposed core; steel rod grouted into hole; core drilled around grouted rod with 100 to 150-mm rock coring drill (same as for ASTM D 2113).	Continuous core reinforced by grouted steel rod	To obtain continuous core in badly fractured, soft, or weathered rock in which recovery is low by ASTM D 2113	Grout may not adhere in some badly weathered rock; fractures sometimes cause drift of diamond bit and cutting rod
Thin-wall tube, ASTM D 1587	75 to 1250-mm thin-wall tube forced into soil with static force (or driven in soft rock); retention of sample helped by drilling mud	Relatively undisturbed sample, length 10 to 20 diameters	In soft to firm clays, short (5-diameter) samples of stiff cohesive soil, soft rock and, with aid of drilling mud, in firm to dense sands	Cutting edge wrinkled by gravel; samples lost in loose sand or very soft clay below water table; more disturbance occurs if driven with hammer
Thin-wall tube, fixed piston	75 to 1250-mm thin-wall tube, which has internal piston controlled by rod and keeps loose cuttings from tube, remains stationary while outer thin-wall tube forced ahead into soil; sample in tube is held in tube by aid of piston (Osterberg-type activates piston hydraulically; Hong-type by a ratchet)	Relatively undisturbed sample, length 10 to 20 diameters	To minimize disturbance of very soft clays (drilling mud aids in holding samples in loose sand below water table)	Method is slow and cumbersome
Swedish foil	Sample surrounded by thin strips of stainless steel, stored above cutter, to prevent contact of soil with tube as it is forced into soil	Continuous samples 50 mm wide and as long as 12 m	In soft, sensitive clays	Samples sometimes damaged by coarse sand and fine gravel
Dynamic sounding (*4.6, 4.12,* Figure 4.15)	Enlarged disposable point on end of rod driven by weight falling fixed distance in increments of 100 to 300 mm	None	To identify significant differences in soil strength or density	Misleading in gravels or loose saturated fine cohesionless soils
Static penetration (*4.6, 4.12,* Figure 4.15)	Enlarged cone, 36-mm diameter and 60° angle forced into soil; force measured at regular intervals	None	To identify significant differences in soil strength or density; to identify soil by resistance of friction sleeve	Stopped by gravel or hard seams
Borehole camera	Inside of core hole viewed by circular photograph or scan	Visual representation	To examine stratification, fractures, and cavities in hole walls	Best above water table or when hole can be stabilized by clear water
Pits and trenches	Pit or trench excavated to expose soils and rocks	Chunks cut from walls of trench; size not limited	To determine structure of complex formations; to obtain samples of thin critical seams such as failure surface	Moving excavation equipment to site, stabilizing excavation walls, and controlling groundwater may be difficult
Rotary or cable tool well drill	Toothed cutter rotated or chisel bit pounded and churned	Ground	To penetrate boulders, coarse gravel; to identify hardness from drilling rates	Identifying soils or rocks difficult
Percussion drilling (jack hammer or air track)	Impact drill used; cuttings removed by compressed air	Rock dust	To locate rock, soft seams, or cavities in sound rock	Drill becomes plugged by wet soil

are between the electrodes, the greater the depth of influence measured relative to the center of the electrode line or spread will be. Dense rock with few voids and little moisture, such as most granites, will have high resistance, but saturated clay will have low resistance. Sometimes the failure surface of a landslide can be detected as a zone of low resistance due to the concentration of moisture. The major advantages of resistivity lie in the portability of the instrument and the fact that large areas can be covered at a relatively small cost. The major disadvantage is that data interpretation is difficult and largely conjectural where strata are not horizontal or uniform in thickness and where contrasts in the resistivities of the materials are not sharp.

Seismic Refraction

The seismic refraction method is based on the measurement of the time required for a shock compression wave to pass from one point to another through the earth. The shock waves are generated by hammer impact or by detonating an explosive at or just below the ground surface. Some of the waves are deflected or refracted by the more rigid, deeper formations and return to the surface where their times of arrival are recorded. In most seismic work involving landslides, a multichannel seismograph system is used. It includes a number of detectors or geophones that are placed at the surface at varying distances from the shock source, amplifiers that enhance the signals, and a recording oscillograph that produces a time-based record of the signals received from all the detectors simultaneously.

When the shock wave from the explosion reaches each geophone, it appears on the recording as a pronounced change in the trace and is termed the first arrival. The time of first arrival at each geophone is used to compute the depth to successively more rigid strata. Seismic measurements are like resistivity measurements in that the environment is not disturbed, the equipment is portable, and rather large areas can be covered at relatively small cost. But, interpretation of seismic measurements, also like that of resistivity measurements, is conjectural where the geology is complex and where velocities of the various materials are not in sharp contrast. The technique is limited to strata that are successively more rigid with depth; it cannot differentiate softer strata below rigid ones.

Gravity

Precise measurements of the earth's gravity field can detect areas of low density. Colluvium or old landslide debris is usually less dense than the virgin materials. Large bodies of loosened rock can be identified where the density contrast is great; boundaries cannot be defined except by borehole logging.

Correlation Representation

The most complete survey or study of an actual or potential landslide is of little value unless it can be depicted in forms that will aid in analyzing and correcting the conditions. These include maps, profiles, cross sections, and three-dimensional representations. Each of these is discussed below.

Geologic Maps

As indicated in the earlier section on geologic reconnaissance, geologic maps provide information on physical features, lithology, and geologic structure. However, existing maps seldom have sufficient detail for the evaluation of an actual or anticipated problem. A geologic map has as its base a topographic map and depicts formations that immediately underlie the ground surface. The projection of each formation to the ground surface is developed from the outcrop mapping and boring data. In problem areas, detailed engineering geologic maps should be prepared on a large scale—the same as that for topographic maps, such as 1:1000 to 1:6000 (1 cm = 10 m to 1 cm = 60 m; 1 in = 83 ft to 1 in = 500 ft). The engineering geology map should also depict features such as rock outcrops, depths to bedrock, strike and dip of beds, faults, and joints, and locations of seeps and springs. The area covered in the detailed geologic map will depend on terrain and topography, alignment and grade of roadway, anticipated soil and geologic conditions, and extent of the slide, if one has already occurred.

Profiles

Centerline profiles of roadway location (made for design) often include data on soil and rock formations as interpreted from geologic maps and borings at representative cross sections. In landslide-prone areas, the number of these routine borings and map interpretations should be increased. The spacings along the centerlines of routine surveys are usually 15 to 150 m (50 to 500 ft). In landslide-prone areas, spacings should be on the order of 8 to 30 m (25 to 100 ft). The profile should show each of the materials encountered in each boring and appropriate additional information, such as moisture content, penetration resistance, strength, and rock core recovery.

Cross Sections

Cross sections, such as the one shown in Figure 4.12, are beneficial in depicting detailed subsurface conditions for landslide studies. These should show soil and rock in and below the slide, dip of the strata, groundwater, moisture contents, and sliding surface or zone of rupture. In all cases, the sections should extend from well into the stable ground above the scarp or crown of the slide to some distance beyond the toe. Geologic cross sections should be plotted by using an undistorted scale (horizontal scale equal to vertical scale); this is essential for a quantitative evaluation of the subsurface geometry that influences the slide.

Three-Dimensional Diagrams and Models

Since landslides are three-dimensional phenomena, the materials and conditions should be viewed in this perspective. To do so, diagrams of the slide from various viewpoints can be prepared in which all available surface information as well as the logs from at least three borings not in a straight line are used. Because of the problem of irregular boundaries and variations in material thicknesses, developing an accurate diagram is difficult. One form of three-dimensional

Figure 4.12. Cross section through center of slide.

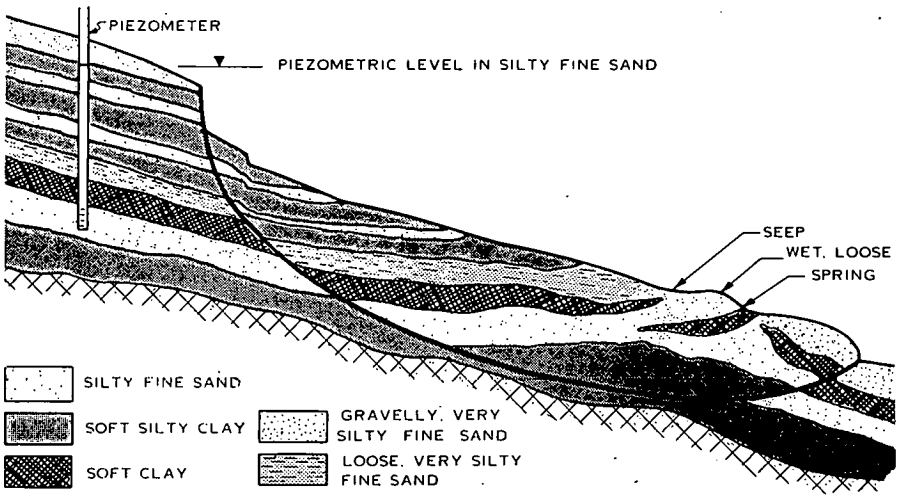
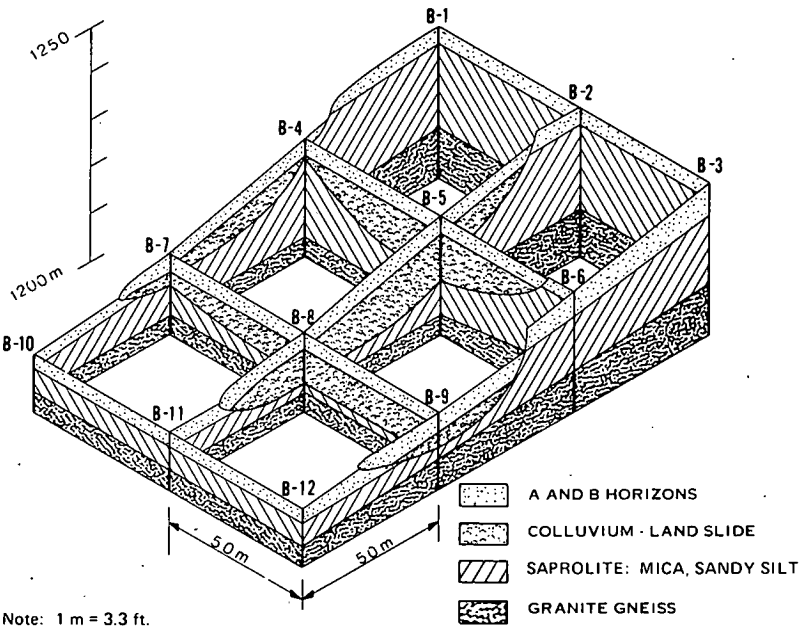


Figure 4.13. Three-dimensional representation of stratification extrapolated from boring.



approach in developing a model involves the use of pegboard and string. The board represents some elevation well below the sliding surface. Holes are drilled in the board to plan scale. Pegs are inserted that represent the borings; the top of the peg is at ground level. The pegs are colored to depict the changes in materials and structure in the boring. The scale in all cases should be the same in all three directions. Strings with different colors or thin plastic sheets can then be laced between the pegs to depict the different boundaries, strata, ground surface, and shear surfaces. Such models can be especially beneficial in the analysis of complex slides or in exhibits for litigation. A fence diagram is a second form of three-dimensional representation (Figure 4.13). The borings are displayed as vertical lines on an isometric plot of location. An exaggerated vertical scale can be helpful in visualizing three-dimensional relations, but it distorts the perspective of the slopes.

Slide Enlargement

Landslides usually continue to increase in size after the initial failure, and the amount of increase can be depicted by using a series of transparent overlays on the original base map or by simply color coding successive new scarps and fractures on the original map. Often there is a considerable time lapse (months to years) between the failure and the correction. In the meantime, the slide sometimes increases in size so that the proposed corrective measures are no longer valid. Thus, it is imperative that the slide continue to be monitored and the displays revised until repair is complete. Some observations should be continued after repairs are made so that the effectiveness of the measures selected can be evaluated and the risk of future movement detected.

SURFACE WATER AND GROUNDWATER

Importance of Water

Next to gravity, water is the most important factor in slope instability. Therefore, identification of the source, movement, amount of water, and water pressure is as important

as identification of the soil and rock strata. Yet, those who conduct the field investigations often pay insufficient attention to water for two reasons. First, the investigative techniques, particularly wet drilling, often obscure groundwater. Second, water conditions change, depending on the weather at the time of investigation and on the cumulative effects of rainfall, snowmelt, surface runoff, infiltration, evaporation, and transpiration throughout the year and during long-term climatic cycles.

Surface Water

In many landslides and potential landslides, the surface runoff is a major factor contributing to groundwater and the soil and rock pore-water pressures that lead to reduced soil strength and movement. Moreover, the diversion or blocking of intermittent and continuous surface streams by the landslide movement can add surface water (which originally flowed elsewhere) to the groundwater in the slide area. The permanent surface-water streams can be identified from aerial photography, particularly with the aid of color infrared photography (Chapter 3). Intermittent streams can be identified as significant water sources only during runoff periods in wet weather. However, the suspicion of intermittent surface water for streams can be raised by topographic details, such as gullying and surface washes.

In some arid regions where the surface-water channels are above the general groundwater table, infiltration from stream beds directly into the ground may be considerable and be aggravated when the stream bed has been loosened, fractured, distorted, or dammed by landslide activity. When water courses appear uphill or adjacent to a landslide, the establishment of flow gauges both upstream and downstream from suspected zones of surface-water loss into the ground is usually prudent. If a stream is very small, a sheet metal V-notch weir and a stilling basin upstream (to establish the appropriate approach velocity) are sufficient. The head is measured by a ruler, staff gauge, or continuous recorder. In larger streams, water-measuring flumes or large weirs may have to be established.

In addition, visual observations of surface water, including sheet runoff, during periods of high rainfall are desirable. An engineer or geologist who can adequately describe and record the flow should make the observations, even though the task is seldom convenient or pleasant. Evidence of sheet runoff sometimes can be found by mud lines and debris that become lodged in tall grass and shrubs. Experience shows that the contributions of sheet runoff and intermittent streams to groundwater and pore pressures influencing landslides are often overlooked in investigations. Securing evidence of surface water and groundwater is a major objective of reconnaissance.

Hints of excessive soil moisture frequently can be found in the character of the vegetation or wildlife in the vicinity of the suspect or sliding area. For example, cattails do not ordinarily grow in low dry areas, and bullfrogs require water for their reproduction and life cycle. The locations of permanent and intermittent surface flows are recorded on topographic maps of the slide or incorporated on map overlays. Attention should be paid to the relation of the changes in these water courses to the continuing changes in the slide and slide area topography.

Groundwater

Groundwater can be defined broadly as all water below the ground surface. Generally, however, the term is restricted to the water that is not restrained in the soil by capillary tension, partially immobilized in the stress field surrounding clay minerals, or linked to the soil or rock minerals. Although soil capillary moisture, absorbed water, and water of hydration may not be considered true groundwater, they are a part of the total ground moisture system. During wet weather, infiltration reduces capillary tension, allowing the groundwater to rise and encompass part of the capillary zone; during dry weather, transpiration depletes capillary moisture, increases capillary tension, and decreases the level of free groundwater. Capillary tension increases the effective stresses among soil particles and temporarily increases soil strength. Loss of capillary tension either by saturation or by drying causes loss of soil strength. An increase in absorbed moisture is a major factor in the decrease in strength of cohesive soils and some weakly cemented rocks. An increase in the water of hydration of minerals such as anhydrite is accompanied by expansion, which can destroy the bonding between soil or rock particles and decrease their strengths. Thus, in most cases, an increase in soil or rock moisture is accompanied by a decrease in strength.

A sudden moisture increase in a dry soil can produce a pore-pressure increase in trapped pore air accompanied by local soil expansion and strength decrease. The slaking or sudden disintegration of hard dry clay or clay-bonded rock is caused both by an increase in absorbed water and by pore air pressure.

Groundwater has been more narrowly defined as that part of the soil-rock-water system that is free to move from point to point under the influence of gravity. The surface of that body of free water, which is at atmospheric pressure, is the groundwater table. In simple terms, the groundwater table is the elevation of zero (atmospheric) water pressure; water is in tension above the water table in the zone of capillary saturation and in the unsaturated capillary fringe, and is under pressure below that table. At any level, the water pressure is equal to the unit mass of water multiplied by the distance (z) below the water table. Above the water table, z is negative and the computed pressure is negative.

Aquifers

In engineering usage, an aquifer is a soil or rock stratum that is significantly more pervious than the adjoining strata. An aquifer can also be an opening in the soil or rock formation, such as an animal burrow, a shrinkage crack, voids left by rotting of vegetation, joints, fracture zones, and other discontinuities that provide localized ability to transmit water. As the term implies, an aquifer contains water, the source of which may be infiltration from precipitation, infiltration from streams, leaking water pipes, or even the upward discharge from a deeper artesian aquifer. Potential aquifers can be identified from detailed records of the soil and rock boring that should describe all of the more pervious strata or fracture systems that are capable of transmitting water. The absolute permeability of the stratum does not determine whether it is an aquifer. Instead, its

relative permeability compared to the strata above and particularly the strata below is more significant. For example, a stratum of silty fine sand could be an aquifer if it were confined between clay strata, but would be an aquiclude compared to a stratum of coarse clean sand. The identification of some discontinuities, such as vertical cracks and joints that are potential aquifers, is more difficult because borings have little chance statistically of encountering them unless the borings are inclined. Test pits and test trenches described in the earlier section on subsurface exploration are far more useful in determining the presence and spacing of such localized discontinuities. A thorough understanding of the geology of the individual formation also provides clues to potential discontinuities that might act as aquifers.

An aquiclude is a stratum or discontinuity that is sufficiently less pervious than the adjoining strata that it is a barrier to groundwater. For example, silt washing into a crack in the ground can produce a clastic dike or aquiclude that will block the flow in a sandy seam. The very movement of a landslide can shift pervious strata to align with impervious strata, generating localized aquicludes. These aquicludes change with the continuing movement of the landslide.

Once potential aquifers have been identified, one must determine whether they transmit water or are subject to water pressure. Long-term observations, particularly during periods of wet weather and high general groundwater levels, are necessary. Moreover, because of changing topography and changing interrelations of the strata with the movement of a landslide, an aquifer today can be dry tomorrow. Therefore, potential aquifers are evaluated by the variations in water pressure as measured by piezometers.

Piezometric Level

The piezometric level at a point is the elevation to which water eventually will rise in a small tube sealed into the appropriate aquifer. The water pressure (u) at a point is equal to the piezometric level (h_{piez}) minus the elevation of the point (h_{point}) multiplied by the unit weight of water:

$$u = \gamma_w (h_{piez} - h_{point}) \qquad [4.1]$$

The water pressure within a soil or rock stratum or crack, as reflected by the piezometric level, is a major factor in shear strength and the most significant single factor in landslide activity. A number of piezometric levels can be defined at any location. Although the two types of water tables (normal and perched) are well recognized by geologists and geotechnical engineers, the multiplicity of piezometric levels present in hillside areas, particularly in areas prone to landsliding, may surprise even experienced groundwater hydrologists.

A normal water table is the level to which the surface water infiltrates in the ground or the level at which the water pressure is atmospheric. Below this level, the groundwater is more or less continuous and pressure increases hydrostatically. A perched water table is one that is sustained above an underlying independent body of groundwater table by an aquiclude. Normal aquifers are sometimes converted to perched aquifers by the rotational movement associated with landslides. The water table changes with rainfall, groundwater flow from outside the area, and movement of the landslide. Thus, the changing nature of a perched water table is one of its most important characteristics.

An artesian aquifer is one in which the level of atmospheric water pressure is higher than the upper surface of the aquifer, but the water is confined by an overlying aquiclude. If the water pressure level in a confined aquifer coincides with that of the aquifer above, a normal water table is present at that instant. However, drainage of the overlying aquifer may not necessarily affect an underlying confined aquifer; thus, a confined aquifer could be normal on one day and artesian on the next, without a change in pressure. Moreover, it might even become perched with more drastic changes in water distribution below the aquifer.

Groundwater Observations

Piezometers

Essentially, a piezometer is a small-diameter well in which the water level or water pressure in an aquifer can be observed. Piezometers have many forms. Simple borings with slotted or perforated casings become observation wells that reflect normal or perched water levels. Wells penetrating into a confined aquifer can measure artesian pressure if the casing is sealed into the aquicludes above. The design and the installation of an adequate system of piezometers require a thorough understanding of the location and permeability of the aquifer and of the surrounding aquicludes. If the volume of water within a piezometer tube or well is large with respect to the flow through an aquifer, the piezometer will be slow to respond to pressure changes. Thus, in aquifers of low permeability or flow, piezometers that require small water volume changes in order to respond to pressure changes are essential. In pervious aquifers, simple holes supported with perforated, screened plastic pipe surrounded by a filter of sand are adequate. Details of typical piezometers and an electric water-level detector are shown in Figure 4.14.

Monitoring Changes

The changing nature of groundwater is well recognized by geologists and geotechnical engineers. Changes in rainfall infiltration and changes produced by groundwater usage are common. However, the changes produced by a landslide are less well recognized. For example, the cracks associated with the landslide may create a more pervious zone of soil or rock that drains well-established aquifers. The opposite may also be true: Aquifers may be blocked by the landslide movements, and thus a normal water table becomes artesian. Groundwater levels must be observed throughout the period of slide investigation. During periods of dry weather, in which there is little movement of the landslide, observations at intervals of a week or two may be adequate. When the slide is moving rapidly, and particularly during and following periods of snowmelt and rainfall, daily, hourly, or continuous readings by a recorder may be desirable to correlate episodes of ground movement with groundwater changes.

Permeability

A knowledge of the ability of a formation to transmit water (permeability) is essential in the planning of drainage systems to correct landslide activity. However, the effects of minor variations in soil texture and particularly the effects of cracks and fissures cannot be easily determined. The permeability of the soil probably varies more from point to point than does any other soil property. Furthermore, the order of magnitude of the variation of permeability in common soils, ranging from gravels to clays, is greater than the variation of the other properties relevant to landslide analyses.

The simplest form of in-place permeability tests is a boring that is cased through the various soil strata down into the aquiclude above the aquifer whose permeability is to be measured. The hole is then drilled into the aquifer. The soil permeability is measured by adding water to the hole to a predetermined level and noting the rate at which the water level drops (*4.17*). The test should be repeated several times if it is suspected that the aquifer is not saturated; otherwise, the inflow during the first few trials may merely represent the filling of empty soil voids. Numerous modifications of this simple approach have been proposed to take into account the penetration of the hole into the aquifer, the hole diameter, and other geometric characteristics. However, experience shows that highly refined analyses of such a simple test are seldom justified.

A better field permeability test involves pumping water into the hole and measuring the rate of flow once equilibrium has been established. The water pressure is measured at several different locations and distances within the same aquifer at points surrounding the hole. Typical distances from the inflow hole are 5 and 15 m (15 and 50 ft); the piezometric holes are aligned in at least four directions. A more thorough investigation involves three sets of piezometers at distances such as 5, 10, and 20 m (15, 33, and 65 ft) and at least four different directions from the inflow hole (*4.14*). If the piezometric level in the aquifer is sufficiently high, a pump-out test can be used instead of a pump-in test. The arrangement of observation wells or piezometers is similar. The test hole must be sufficiently large so that the pump can be placed inside it; otherwise, the water can be lifted only about 8 m (25 ft). Pump-out tests are sometimes more reliable than pump-in tests because any soil fines that accumulate in the well are flushed out by the flowing water. In pump-in tests, those fines can accumulate in the soil or rock pores and give a false indication of low permeability. In pump-in tests, care must be taken not to contaminate an aquifer that is used for drinking water. For example, river water for pump-in tests should be chlorinated.

If the groundwater is definitely discharged through seeps and springs whose flow can be collected and measured, the permeability of an aquifer from those discharges and the gradient found within the aquifer may possibly be estimated by a grid of piezometers. Typically, the flow is downhill through an aquifer toward the toe of the slope. The piezometers, therefore, should be in lines parallel to the direction of maximum slope in order to measure the hydraulic gradient. Of course, a single piezometer might be introduced into the aquifer on the assumption that the water pressure at the point of exit is approximately atmospheric. However, the actual water pressure just within the aquifer at the point of exit is usually greater than atmospheric, and such estimates are likely to be high. When several such determinations are made, they can yield the order of magnitude of the permeability of the stratum under its natural conditions of flow.

Springs and Seeps

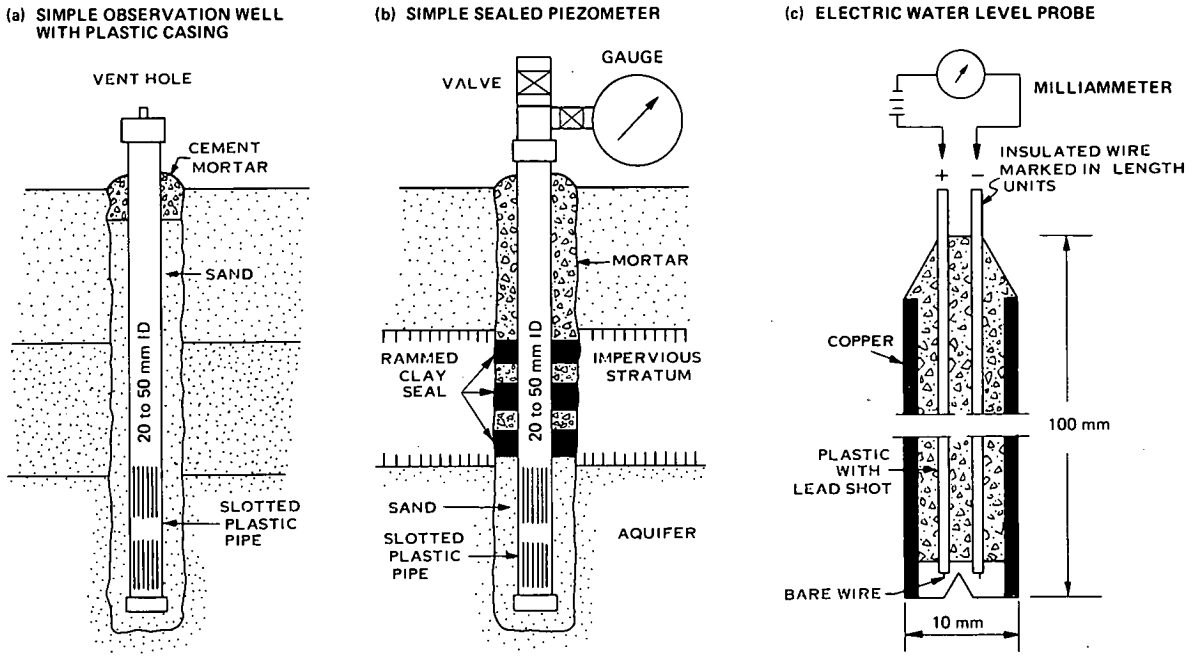
The intersection of an aquifer with the ground surface produces either a concentrated flow in the form of a spring or a diffused flow in the form of a seep. Both of these represent the exit or discharge of the aquifer and may be regarded as safety valves for the release of groundwater pressure. So long as springs or seeps flow freely, an unusual buildup of groundwater pressure in the aquifer that supports the spring or seep will not be likely. If the rate of discharge of the spring or seep is known and if the permeability of the formation can be estimated, an estimate is even possible of the pore-water pressure within the aquifer at varying distances within the hillside. Unfortunately, engineers and geologists who evaluate landslides often regard a spring or seep as a causative factor (it can be, if the effluent of a spring above a slide infiltrates downhill into the slide zone), but generally the total effect is more beneficial than detrimental. For example, a sudden stoppage of a spring or seep may be the precursor of landslide activity. Increased flow in a seep or spring frequently indicates that an aquifer is draining, the piezometric pressures are reducing, and the stability is increasing. Springs and seeps suggest which potential aquifers contain water and could be involved in the buildup of pore-water pressure. Thus, a spring or seep once located should be identified with the particular soil stratum or rock formation that produces the flow.

A significant discharge of a spring or seep should be collected and the quantity monitored by a V-notch weir or similar device. The discharge from small springs can be collected by use of 5 to 10-cm (2 to 4-in) plastic pipes embedded in gravel-filled collecting wells. The flow can be piped to a buried oil drum, which serves as a catch basin for silt; the edge of the oil drum can be cut to form a V-notch weir, which serves as a measuring device. It is sometimes helpful to install a continuous water-level recorder to indicate rapid changes in the spring or seep discharge. As previously pointed out, infrared photography, as well as thermal sensing, can show where springs and seeps are located, even though they may be partially obscured by vegetation or colluvium cover.

Correlation

The location of aquifers and springs or seeps should be shown on both the topographic maps of the landslide area and the various landslide cross sections that are plotted from topographic data. Since water coming either from runoff or from infiltration or groundwater originating elsewhere is a major factor in most landslides, the evaluation of the groundwater aquifers and the changes in the piezometric level are a vital part of the investigation. Unfortunately, experience shows that these groundwater changes seldom

Figure 4.14. Groundwater observation devices.



Note: 1 mm = 0.04 in.

are evaluated in sufficient detail to obtain a complete picture of the factors leading to landslide activity.

ENVIRONMENTAL FACTORS

Both natural and human changes in the environment have a profound effect on landslides. The history of the area, both during human occupation and during recent geologic times, determines the conditions leading to land movement; moreover, as mentioned previously, the historical behavior provides clues to potential instability. Therefore, the total environment must be investigated to provide both the historical background and a key to future changes.

Weather

The climate of the area, as expressed in the various components of weather, is the ultimate dynamic factor influencing most landslides. The data ordinarily available for landslide investigations from weather stations within 100 to 200 km (60 to 120 miles) include rainfall (15 min, hourly, and daily), temperature (daily maximum and minimum and daily and monthly mean), evaporation (daily and monthly), wind (maximum, hourly, daily, and monthly), snowfall (daily and monthly), relative humidity (daily and monthly), and barometric pressure (maximum and minimum daily). Unfortunately, the weather station may be too distant for the data to be fully representative of the site. The effects of these factors can seldom be evaluated analytically because the relations are too complex. Empirical correlations of one or more of the weather factors (particularly rainfall, snow, and melting temperatures) with episodes of movement or movement rates can point out those environmental influences that must be controlled to minimize movements.

Human Changes Before Construction

Many areas of the world have been altered by human activities, such as terracing for agriculture, diversion of streams, mining, leveling for housing and industrial construction, and cuts and fills for highways, airfields, and railroads. Another human activity is alteration of the groundwater table. The piezometric level is lowered significantly by wells. In areas adjacent to large cities that depend on groundwater or in areas in which wells are used for irrigation, the level has been depressed more than 100 m (300 ft); the affected area may extend for many kilometers. This lowering of the piezometric level within the soil and rock imposes an increased effective stress, which in some instances contributes to the stability of the slope. Paradoxically, lowering the groundwater table can also trigger sliding because of the difference in the total and buoyed weight of the soil. Draining land for agriculture may lower the water table, but this is seldom of significance in landslides because such drainage is generally in bottomlands, which are not subject to sliding.

A rise in the water table can ultimately have an adverse effect on slope stability. Such a rise may occur around small towns that begin to use surface water instead of groundwater to meet increased water demands. Irrigation in arid regions has significantly elevated the groundwater table and thereby significantly decreased the strength of soils that are cemented by water-soluble agents such as calcium carbonate or dry clay. For example, in certain areas of India, hilly land, which for years had been stable, suddenly became landslide-prone after irrigation began. In one area of the Himalayas, a mountain road was destroyed each year by landslides for a distance of about 10 km (6 miles) because of irrigation of the terraced mountainsides above. The irrigation water penetrated through the closely jointed

rock and produced flow slides. Similarly, water impoundments can raise the water table and change the stability of nearby hillsides. For example, a highway fill across a reservoir suddenly experienced sliding when the soil was saturated at high water levels, and then stress and localized pore-water pressure increased when the reservoir was rapidly drawn down.

Changes in slope by excavation and filling in the vicinity of the study area may give clues as to the long-term effects of excavation and filling. For example, some rocks, such as shale, are hard and strong when first excavated. However, exposure to air and changing weather causes the shale to break down, soften, and slide. Such failures have been experienced in the Appalachian Mountains, on the eastern flanks of the Rocky Mountains, and along the Pacific Coast. Although older cuts and fills may not be so deep as those currently contemplated, they sometimes exhibit symptoms of long-term deterioration. Their overall performance, particularly local sliding, constitutes full-scale, in-place tests of the physical properties of the soil and rock. Such tests are more reliable indicators of future stability than the short-term laboratory tests that are customarily made to evaluate potential sliding.

A reconnaissance of older cuts and fills is recommended to evaluate the stability of human changes in topography. Calculations based on information regarding unstable areas will provide valuable data on the ultimate strength of the materials and on the degree and rate of change that can occur because of weathering. This reconnaissance of existing cuts and fills has been sorely neglected in most landslide studies, yet the data obtained are probably the most reliable of all in evaluating the strength of the materials. To make a valid correlation between the performances of old cuts or fills and those proposed requires that the geologic similarity of the two areas be established. Moreover, the climate at the area of old construction must be correlated with that at the new area if the older area is not in the immediate vicinity of the site under construction.

Changes Brought by Construction

New construction in areas in which landslide activity is suspected or has commenced should be monitored to determine whether changes predicted by studies made before construction actually occur, to evaluate the methods used in such studies, and to predict future landslide activity in an area where movement is just commencing. The major purpose of monitoring, however, is to determine what changes the construction actually produces. Because changes in the design of slope and drainage features are often made in the field, the completed project is usually different from that shown in the plans and specifications. Moreover, fills may not be compacted as specified or intact materials in virgin cuts may be loosened by uncontrolled blasting. Sometimes, the person responsible for changes in the plans and specifications will take no notice of them because of ignorance of their importance or will hide them because of fear of criticism or recrimination. Thus, the investigator has difficulty in finding out exactly what changes might have been made to the provisions of the plans and specifications and is often placed in the position of a detective ferreting out information.

A detailed study of the daily logs of inspectors, daily reports of project superintendents, records of blast-hole advance and explosives used, and journals of the contractor will provide clues to the actual construction conditions. Sometimes these records contain references to springs that have been covered by embankments, references to unsuitable materials that have been inadvertently placed in fills, and evidence of overblasting or movements that have been forgotten in the scramble to complete construction on time. The written records supplemented by personal interviews often provide the best clues to the factors that triggered landslide activity.

Effect of Ecosystem on Sliding

The biological environment of the site plays a part (although usually minor) in the behavior of a landslide. For example, a good vegetation cover promotes infiltration of rainfall and minimizes surface runoff and local gullying. The effect of the increase in the local groundwater by infiltration may be less serious than that of the concentrations of stress by local gullying. A thick mat of vegetation will also reduce the amount of water that becomes groundwater by enhancing water loss due to transpiration. Of course, during cold periods and periods of snowmelt, the water loss by transpiration is negligible.

The reinforcing effect of a strong root mat is significant in the scarp area of landslides. In some marginally stable slopes, the root mat can be the difference between sliding and creep. Moreover, a well-developed root system significantly reduces retrogression of the scarp up the hill. In highway excavation, the root mat may be affected by factors other than the slope. For example, the intercepting ditch, which is sometimes excavated above a deep highway cut on a hillside, may cut through the root mat and become the focal point for future sliding. Haul roads above cuts similarly damage the roots and promote local sliding, which leads to retrogression.

Animal burrows may also play some part in small slides. For example, the interlacing burrows of rodents can weaken the soil and provide channels for concentration of surface water and its infiltration into the ground. However, there is little documented evidence of such effects.

Overgrazing of hillsides reduces the vegetation cover and frequently promotes more rapid infiltration and localized sliding, which then triggers more profound movements, particularly in semiarid regions where vegetation does not recover rapidly from the overgrazing and where the rainfall may be extremely intense during short periods.

Effect of Sliding on Ecosystem

Landslides may also change the ecosystem of an area. Groundwater flows are altered by landslide movement; locations of springs and seeps change, and these changes are reflected in differences in vegetation. For example, wet-area vegetation, such as cattails, often develops within a few months in the depressed areas commonly associated with landslides. Similarly, the cracks and the scarp areas above a landslide provide local drainage of the topsoil and an associated loss in the ability of this material to sustain growth of vegetation during periods of dry weather. Thus,

scarps that are hidden by vegetation are revealed by a reduction in the vigor of that vegetation. This can be sensed by color infrared photography during dry weather. On the other hand, in areas of bare rock, open joints in which moisture is trapped and roots penetrate provide the only zones that can sustain life. In one particular major rock slide in a steep mountainous area, the joints were clearly delineated by lines of small shrubs, but the remaining rocks were bare. Those joints became the scarps of multiple rock slides. The continuing enlargement of uphill joints above the rock slide could be seen in the gaps between the root mats and the walls of the cracks. Thus, a study of the vegetation of an area may provide supplementary clues to the rate of earth movement and its focal points, such as seeps, springs, cracks, and fissures in the ground.

FIELD TESTING

To evaluate the potential stability of a slope that has not failed or to assess the effectiveness of corrective measures for a slope that has failed requires that the physical properties of the materials involved be measured. Of course, measurements are most conveniently done in laboratory tests of undisturbed samples secured from the site, but obtaining representative samples is difficult for a number of reasons.

1. Discontinuous samples with relatively small diameters can miss thin critical strata (such as the slickensided surface of movement of an ancient slide) that control sliding.
2. The laboratory tests can integrate neither the effects of the discontinuities, such as cracks, within the soil nor the effects of localized hard spots, such as gravel, in a clay matrix.
3. Distortion, disturbance, and moisture and stress changes are always associated with taking a sample out of the ground, handling it, transporting it, and preparing it for laboratory testing.

To eliminate these difficulties, various in-place tests have been devised. An important difference between laboratory and in-place tests is their relation to the initial in situ state of stress. A laboratory test must often reproduce this state of stress whereas a field test inevitably begins at this state of stress. In either case, the in situ state of stress must be evaluated, which is often difficult and expensive. For some soil deposits, such as a deep, normally consolidated clay with a horizontal surface, the horizontal stress will be a fraction of the vertical stress, depending on the coefficient of earth pressure at rest. Unfortunately, such a simple situation is seldom valid for landslide studies because the ground surface is not level and other significant stresses may be imposed by desiccation, artesian water pressures, tectonic forces, residual forces from strains produced by past earth movements, and changes produced in any of the above by erosion or construction.

The fact that any in-place test must be conducted with reference to the existing in situ state of stress is an important limitation in itself. Although the stress field is altered somewhat by boring or introducing some testing device into the soil, the existing stress field cannot be changed significantly. Thus, in-place testing usually cannot simulate the large changes in stress that accompany environmental changes, cutting, filling, and landslides. Although laboratory tests can simulate an almost unlimited range of stress changes, the sample tested has already been subjected to a significant stress cycle (unloading during sampling and reloading during testing) that is not necessarily similar to the stress changes involved in a landslide. These inherent stress limitations of both in-place and laboratory tests must be understood by those who use soil or rock test data in evaluating slides.

Borehole Tests

Certain tests have been devised to be performed in the same bore holes that are drilled for identifying the soil strata and for securing the small-diameter samples. Although borehole tests suffer from the limited volume of material tested, they do allow the soil to be tested without the disturbance produced by removing the sample from the ground, taking it to the laboratory, and preparing it for testing. However, some disturbance and sloughing are caused by stress relief in the bore-hole walls.

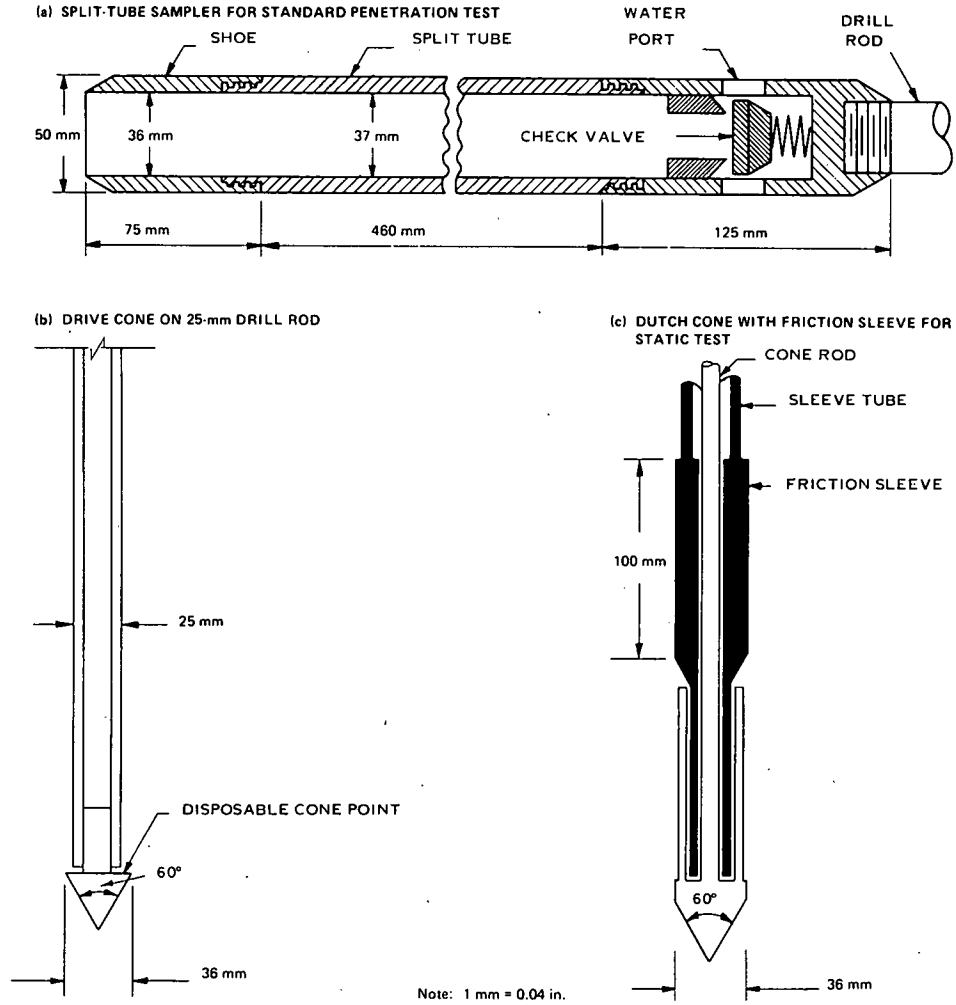
Dynamic Penetration Test

Driving a device into the ground by impact measures the resistance of the soil to rapid or dynamic displacement. Thus, it indirectly measures shear strength under the same form of impact loading produced in the test. If the dynamic and static shear strengths are similar, the test can be an indicator of the static shear strength, which may also be empirically related to other soil properties, such as the relative density of sands or the compression index of clays. Typical correlations are summarized by Sowers and Sowers (*4.14*).

The standard penetration test (ASTM D 1586) is an adjunct to split-tube sampling. A split-tube sampler 37 mm (1.4 in) ID, 50 mm (2 in) OD, and 660 mm (26.0 in) long (Figure 4.15) is driven 450 mm (18 in) in three 150-mm (6-in) increments into undisturbed soil at the bottom of a borehole by blows of a 63.5-kg (140-lb) hammer falling 760 mm (30 in). The sum of the blows for the second and third increments is the standard penetration resistance (N); it is expressed in blows per 300 mm (blows per 1 ft). Before the test, the sampler is seated 20 to 40 mm (8 to 16 in) in the hole bottom. Because of cuttings or other weakened material in the bottom of a bore hole, the first 100 to 150 mm (40 to 60 in) may not be meaningful. Therefore, the standard penetration test includes gaps in the penetration resistance record. The N-value encompasses both hard and soft seams in the 300-mm distance. Although some investigators have attempted to drive such sampling tubes as far as 1.8 m (5 ft), counting blows for each 150-mm increment, the accumulating skin friction and the buildup of soil resistance within the samples usually produce resistances that increase with each successive increment until the sample is withdrawn and the borehole cleaned out.

A more sensitive dynamic test involves driving a cone point that is 25 to 100 mm (2 to 4 in) in diameter and has a point angle of 60° into the soil by means of a weight [typically 50 to 100 kg (110 to 220 lb) falling 0.5 to 1 m (1.5 to 3 ft)]; the drive rod is 25 to 30 mm (1 to 1.2 in) in

Figure 4.15. Penetrometers.



diameter. By such a procedure, the penetration resistance for each 100 to 300 mm (4 to 12 in) can be measured without the accumulation of soil friction along the drive rod. In many soils, a 50-mm (2-in) point driven with the 63.5-kg (140-lb) hammer falling 760 mm (30 in) gives penetration resistances for 0.3 m (1 ft) of driving that are equivalent to N. The drive cone on a 25-mm rod is also shown in Figure 4.15.

Dynamic penetration resistance is generally correlated empirically with soil properties measured by either laboratory tests or field tests of the same material. In this way, large numbers of low-cost penetration tests supplement the more limited information obtained by more expensive laboratory tests. Although many relations between resistance and soil properties such as angle of internal friction in sands and undrained shear strength (cohesion) of saturated clays have been published (*4.14, 4.16*), these should not be used indiscriminately. Instead, a new correlation should be established from the data obtained on the site in question, or the data should be used to verify the accuracy of the published relations (*4.5, 4.13*).

Static Penetration Test

Static penetrometers measure the resistance of the soil to displacement of a point by a static or slowly increasing load. Most tips are in the form of cones having point angles ranging from 30° to 90° and diameters from 36 to 50 mm (1.4 to 2 in), as shown by Hvorslev (*4.6*). One form of cone widely used in the Netherlands and generally termed the Dutch cone employs a cylindrical sleeve that is 100 mm (4 in) long and 36 mm (1.4 in) in diameter and is above a 60°, 36-mm (1.4-in) conical point, as shown in Figure 4.15. The cone is forced ahead slowly by a steady pressure that is measured. Simultaneously or successively, depending on the design, the frictional resistance of the sleeve against the soil is measured. The cone directly provides information on the point bearing capacity of the soil. It can be interpreted in terms of the point bearing of piles. Although at one time the cone resistance of soil was believed to be identical to that of a pile, experience has shown that cone resistance may be double that of piles. The cone does provide detailed information on the relative strength of the soil at small intervals. For example, some cones have an electronic readout that generates a continuous graph or electromagnetic tape showing both cone resistance and sleeve resistance as a function of depth. The record is well suited to identifying weak zones, such as the shear surface of the slide, which may be less than a few centimeters thick. By way of contrast, conventional sampling might not find such a thin zone of weakness. The ratio of cone resistance to sleeve resistance is an indicator of the type of soil (*4.12*). The cone penetrometer is an extremely valuable supplement to the more direct boring and

sampling techniques. It helps to identify changes in stratification and to pinpoint weak materials that should be investigated in more detail by direct methods.

Borehole Dilation Test

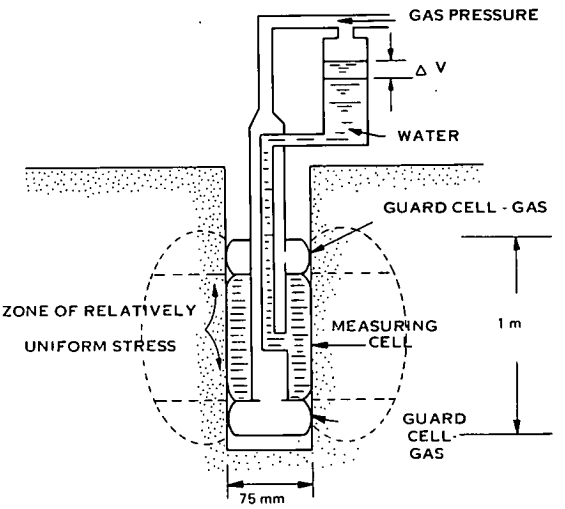
A number of field tests have been based on the resistance of a cylindrical borehole to dilation from applied internal pressure. The best known of these is the Menard pressuremeter (Figure 4.16). Most devices use a cylindrical rubber tube that closely fits the inside of the borehole. The tube is inflated with a fluid under pressure, and the expansion of the hole is measured by the volume of fluid that exceeds that required to fill the original hole. A plot of fluid volume (converted to hole diameter) as a function of pressure is used to compute the in-place deformation characteristics of the soil; the results may be interpreted to determine the in-place shear strength. In the Menard device, the end effects in the measuring cylinder are minimized by means of additional similar cylindrical rubber tubes above and below; these tubes are inflated to the same pressure as the test cylinder, thereby providing a two-dimensional stress configuration rather than a three-dimensional one, which has a more complicated elliptical zone of strain. Other similar devices omit the end tubes and depend on the theoretical interpretation of the elliptical zone of stress and strain. Still others employ mechanical sleeves and strain sensors to measure pressure and displacement.

Although it is claimed that such devices can provide the user with all of the necessary soil properties to evaluate shear and consolidation, the interpretation is largely empirical and certainly open to question in variable materials. Typically, the lengths of these devices limit the stress zone to a length of about 0.6 m (2 ft) and diameter of about 0.3 m (1 ft). The use of the test results without confirmation by other means would be unwise.

Borehole Shear Test

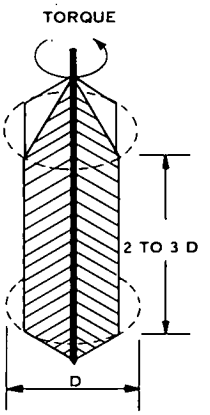
The borehole shear test measures the shear strength of the soil in an annular zone surrounding the boring. The device consists of an expandable plug with serrations on its outer surface to grip the soil walls of the hole when pressure of known magnitude is applied internally by a hydraulic system. The soil is then sheared by pulling the device upward through the hole. If several such tests (essentially undrained direct shear) are made on the same stratum at varying internal pressures, the Mohr failure envelope can be obtained. The test is limited because it shears the soil in a different direction than that involved in the landslide process. Therefore, if the soil has anisotropic properties (usually the axis of weakness is parallel to the greatest extent of the surface of shear movement and more or less perpendicular to the direction of shear in the borehole shear tests), the results may be misleading. There is usually some soil smear in the walls of the borehole; thus, the soil involved in the test may be partially disturbed. However, the disturbance from this cause is likely to be less than that resulting from rough handling of soil samples. The size of the device is such that it integrates the effect of soil irregularities over a cylindrical surface with a diameter of 76 mm (3 in) and a length of about 300 mm (12 in).

Figure 4.16. Menard pressuremeter for borehole dilation test (not to scale).



Note: Gas in guard cells; water in measuring cell.
1 m = 3.3 ft; 1 mm = 0.04 in.

Figure 4.17. Vane device.



Vane Shear Test

Vertical blades at the end of a thin rod produce a vertical cylindrical surface of shear when rotated (Figure 4.17). The torque required to initiate continual rotation is a measure of the peak undrained strength of the soil, and the torque required to maintain rotation after several revolutions measures the residual or disturbed strength. To minimize end effects, the length of the vane should be at least twice its width. The blades should be sufficiently thin that there is a minimum soil disturbance due to displacement and sufficiently thick that they do not bend under load. In very soft soils, the vane and its torque rod are forced into the soil to each level to be tested. A reference test using the torque rod without the vane is required so that the torque necessary to overcome rod friction can be subtracted from the total torque measured when the soil is tested. In firm soils or at great depths, the test is made in undisturbed soil 300 to 760 mm (12 to 30 in) below the bottom of a bore hole; hence, the resistance of the torque rod in the hole generally is negligible. Numerous procedures and forms of equipment, ranging from simple torque wrenches to elaborate torque meters that apply a uniform angular

strain rate, have been utilized (*4.6*). Our opinion is that the increased accuracy of the results does not justify the use of elaborate procedures and complex equipment. Caution should be exercised when one interprets the peak strength; in some cases, the strength measured in a vane test has been found to be as much as 30 percent greater than that measured by other methods. Moreover, safety factors computed from such strengths have been found to be unrealistically high. Vane data should be correlated with other shear data for use in analysis and design.

Large-Scale Pit Tests

As previously stated, one of the major limitations of laboratory tests is their inability to integrate the variations in the soil, particularly in zones with weak or hard spots. This can be overcome by large-scale, in-place tests performed in pits or trenches excavated to the questionable strata or zones of slickensiding. Although the range of stresses and particularly the range of groundwater pressures that can be evaluated by such tests are limited, the tests permit large volumes of soil to be evaluated under the conditions present within the total mass without the problems of sample disturbance and exposure inherent in small-scale sampling and laboratory testing.

Load Test

The oldest form of in-place test is the plate load test (*4.14*). A pit is excavated to the surface of the stratum in question, and a rigid square or circular plate is placed on the ground. Its width should be as great as possible, but no wider than about two-thirds the thickness of the stratum whose strength is to be evaluated. The plate is loaded incrementally so that at least 10 successively greater loads are applied before the plate shears the soil beneath it. The results of such a test can be interpreted in terms of soil bearing capacity to give the shear strength of the soil along a curvilinear surface (which may crudely approximate the failure surface of a landslide). However, there are many different interpretations of such tests, all yielding different values for the shear strength parameters. Therefore, the test has limited value in determining the strength of the soil involved in the instability of large earth masses.

Large-Scale Direct Shear Test

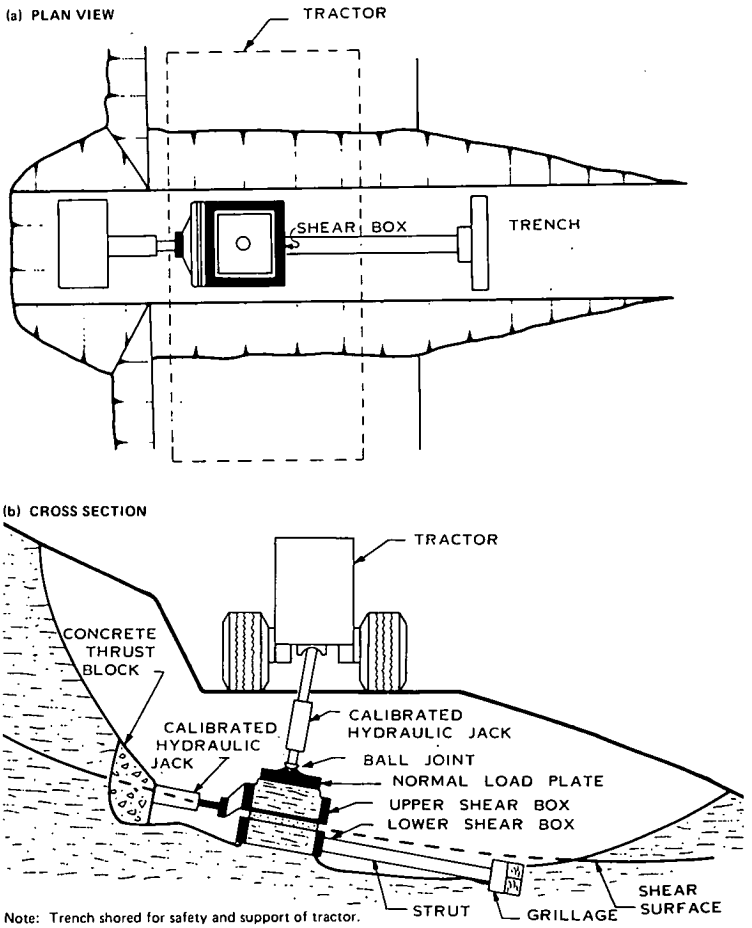
A large-scale direct shear test can be performed in a pit at the level of the suspected weak stratum; in the case of an existing landslide, the test may be performed on the actual failure surface of the soil. The pit is excavated to the level of the stratum or shear surface to be evaluated and should be large enough to allow engineers and technicians to work around the sides without disturbing the soil to be tested in the center. All the soil within the pit is excavated, except that to be tested, which is left in the form of a block or crude stump above the bottom of the pit. The size of the block is dictated by the engineer's or geologist's evaluation of the variations of soil strength. It should be large enough to be representative of the stratum as a whole and not just its weaker or stronger segments. A double box is placed around the block in question. If there is a definite plane of weakness, the sides of the box should be perpendicular to that plane, and the plane should lie between the top and bottom halves of the box. Such a test setup is shown in Figure 4.18. Good contact is secured between the soil and the box either by careful trimming of the soil or by pouring plaster to fill the space between the box and the soil. Because of the difficulties in trimming gravelly soils or soft rock, the plaster filling is recommended.

A normal load is placed on the block to be tested by means of a plate, the dimensions of which are slightly smaller than that of the box, fitting just inside the upper half of the box. The load is applied by jacking against a piece of heavy machinery above the pit or against a heavy steel beam anchored to the ground by earth anchors. The anchors must be sufficiently far from the test zone so that the stresses around them do not influence the test. The bottom half of the box is anchored securely in place by packed soil, concrete, or plaster in the bottom of the test pit. The top half is then jacked sideways by a calibrated system so that the amount of lateral movement and the load causing the movement can be measured. The direction of jacking should be parallel to that which is suspected in a potential landslide zone or parallel to the movement that has occurred in an actual landslide (as indicated by slickensides on the shear surface). The same surface can be tested at several different normal loads if the test for each vertical load increment is stopped soon after peak strength or significant movement develops. At this point, a larger normal load is applied and the test is resumed. Such a direct shear test determines the average shear stress required to produce failure on a predetermined failure plane. If the peak strength of the soil must be determined, separate tests should be performed on fresh sample blocks for each normal load applied. This will require a large test trench or more than one test pit.

The results of a large-scale shear test simulate the shear strength of the soil along an actual failure surface. The results integrate the effects of both hard and soft zones if the test sample is sufficiently large. Unfortunately, it is difficult to include the effects of changing water pressure. However, our experience shows that meaningful shear test data have been obtained from such tests, particularly if done during the wet season. Correlating the results of an in-place test with those of smaller laboratory tests on similar soils makes it possible to extend the data obtained from the in-place tests to include the effects of changing water pressure introduced under controlled laboratory conditions. Thus, a more reliable combination of data for evaluating the strength of the soil mass involved in the landslide is provided by a combination of judiciously selected large-scale field tests and laboratory tests than by laboratory tests alone.

Standard equipment for making such tests is ordinarily not available. Instead, the equipment is fabricated to fit the size of the sample needed for the particular situation, the space available within the test pits or trenches, and the geometry of the shear surface. It can be improvised out of steel angles, channels, and plates at a reasonable cost. The loading is provided by calibrated hydraulic jacks or jacks with load cells; and the movements are measured by micrometer dial gauges. Although such measurements may be characterized as crude, their lack of precision is more

Figure 4.18. Direct shear test of strength along failure surface. (a) PLAN VIEW



Note: Trench shored for safety and support of tractor.

than compensated for in their realistic representation of field conditions.

Borehole Dynamics

The effect of a landslide on a borehole, particularly in squeezing or shearing, can be a valuable indicator of rates of movement and locations of shear surfaces. Although equipment for measuring such changes is available, much meaningful information also can be obtained from drillers' observations in those borings that are not instrumented. Among the factors to be observed are loss of drilling fluid, gain of water or fluid, gas, squeezing of hole, damage to drilling tools, loss of samples, blocking of cores, drill rod drop, broken core, slickensided samples, and unusually weak zones.

Geophysical Tests

The geophysical studies previously described can be used not only as a means to define the stratification but also as a direct measure of certain physical properties of the soils. Although these properties may not necessarily be those needed to evaluate stability, an empirical correlation among the properties of interest can sometimes be established in the stability analysis of the landslide.

The seismic refraction technique yields the compression wave velocity of the soil or rock. If the density is known, the dynamic modulus of elasticity in compression can be calculated. Since the density of various soils and rocks does not vary greatly from point to point, calculations based on estimates may be sufficiently reliable for estimates of the rigidity of the mass. The seismic compression wave velocity is particularly valuable as an indication of discontinuities in rock, because it is reduced by cracks or microfissures.

The refraction technique does not allow identification of a weak fractured zone beneath a sounder, higher velocity stratum. However, this identification can be done by cross-hole seismic measurements, utilizing borings from 3 to 12 m (10 to 40 ft) apart. The seismic impulse is generated at the depth of the stratum measured by an explosion, and the time required for the shock wave to travel through the material is measured in the second hole by a geophone suspended at the level of the stratum in question. Although engineering properties relevant to landslide evaluation, such as shear strength, cannot be determined directly by such techniques, the suspect stratum can be identified and a crude empirical correlation can be developed between seismic velocity and engineering properties. Below the water table the compression wave velocity in materials of low rigidity is obscured by the compression wave velocity in water.

The apparent resistivity of a soil can be related empirically to soil type and soil moisture. An aquifer with highly ionized water exhibits a far lower apparent resistivity than a dry stratum in which the minerals do not ionize readily. For example, the shear surface within a landslide frequently

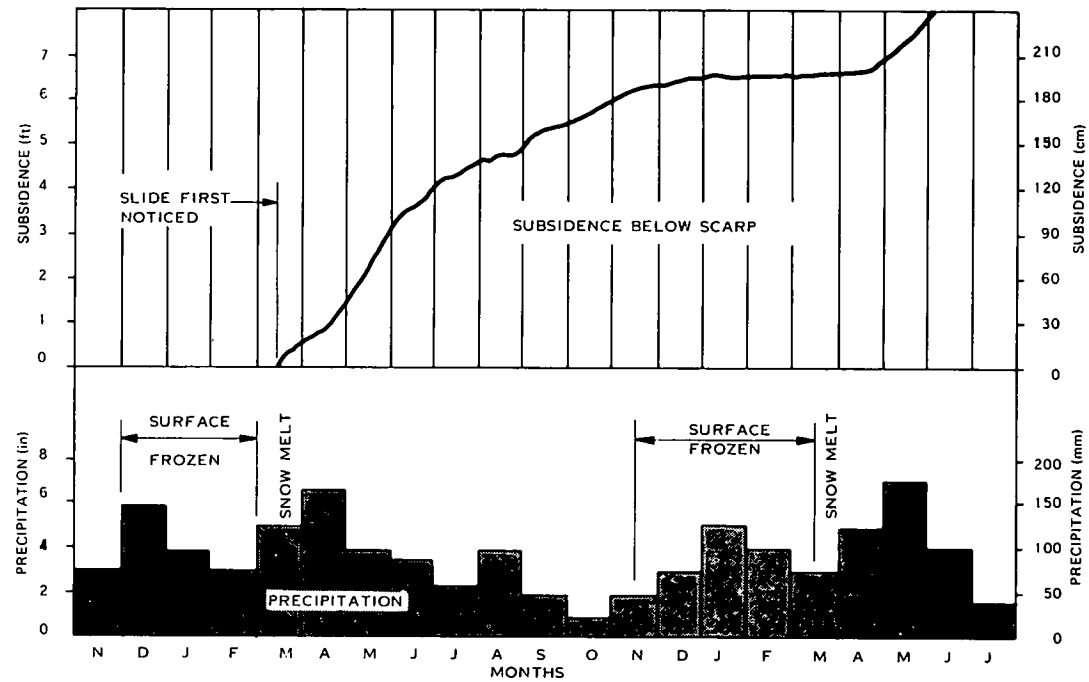


Figure 4.19. Correlation of slide movement with precipitation.

exhibits a marked lower electrical resistance than the surrounding intact soils, probably because of the disturbance of the minerals and the accumulation of water along the shear surface.

At best, however, geophysical tests are only indirect supplements to the more direct means of evaluating the qualities of the soil and rock in place. The tests are simple, can be performed in a short period of time, and are relatively inexpensive. However, interpretation of the results must be done with extreme caution; too often interpreters jump to conclusions and obtain misleading results.

CORRELATION OF DATA

During an investigation, considerable data will be accumulated. The variations of these data, which may occur randomly or in some definite pattern, should be studied in three dimensions because the mass of soil or rock involved in a landslide is three dimensional. Some of the ways in which this can be accomplished are discussed briefly below.

Areal Variations

Some of the data obtained will vary with geographic position. These data can be depicted best in the form of maps. If the variations in the data are systematic, they can be depicted as contours, such as lines of equal strength or lines of equal groundwater pressure. These variations are frequently plotted on overlays to the topographic map of the site; several overlays may be desirable.

Cross Sections

Depicting the data in the form of cross sections is particularly useful because the stability of the mass is usually evaluated by use of cross sections (Figure 4.12). Cross sections parallel to the direction of the maximum slope, to the maximum water pressure gradient, or to the observed trajectories of movement are the beginning point for a stability analysis of an earth mass. The various strata encountered and the groundwater levels or pressures are depicted on these cross sections. In addition, overlays should show the engineering properties relevant to the stability analyses. The surfaces of failure, as deduced from ground surface observations, sophisticated instrumentation, borings, test trenches, and pits, define a body of soil on which various force systems act. The external forces depicted on an overlay to the cross sections provide the beginnings of the analyses described in Chapter 7.

Time-Based Observations and Correlations

The significance of the different factors involved in a landslide can frequently be found from empirical correlations between movement and observed forces or environmental factors. For example, a time-based graph of both landslide displacement and rainfall or accumulated rainfall and snowmelt may show a visual relation (Figure 4.19). Similar time-based relations can be observed between construction operations and movement. In some cases, plots of the observed phenomena as functions of the logarithm of time are instructive. For example, stochastic processes, such as the readjustment of coarse particles through creep and secondary soil compression, often can be approximated by a straight line on a plot of movement as a function of the logarithm of time. Thus, the time graph or the logarithm of the time graph becomes a diagnostic tool in analyzing the causes of movement.

CONCLUSIONS

The field investigation identifies potential problem areas and defines the features involved in an existing landslide.

More intensive investigation uncovers the soil and environmental factors that produced the movement. The mathematical analysis of a landslide is based on the field investigation and obviously can be no more accurate than the data obtained from the field work; likewise, the corrective measures based on the analyses can be no more effective than the quality of the data used in the analyses. Unfortunately, our experience has been that field investigations are often inadequate and that geologists and engineers sometimes jump to conclusions before the data have been obtained and evaluated; thus, they merely perpetuate their past mistakes. A technically sound solution can be derived only from technically sound data.

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PHOTOGRAPH CREDITS

Figure 4.8 Courtesy of Tennessee Department of Transportation
Figure 4.9 Courtesy of Tennessee Department of Transportation