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ABSTRACT

Slope Stability is one in a series of single-topic problem modules intended for use in undergraduate and earth science courses. The module, also appropriate for use in undergraduate civil engineering and engineering geology courses, is a self-standing introduction to studies of slope stability. It has been designed to supplement standard introductory geology laboratory exercises, providing text, problem, and laboratory materials sufficiently flexible to satisfy the needs of widely varied classrooms and instructional situations. Background information may be supplemented with material in other texts. Problems may be done independently of or in conjunction with the laboratory exercises. Topics (with related text, problems, experiments) focus on forces at work, nature of materials, nature of movement, mass-movement classification, landslide recognition, stability analysis, landslide control/correction. Additional, miscellaneous experiments (man-made slope instabilities, quicksand, piping, rapid reservior drawdown) and examples of types of mass movement are provided. Module equipment/materials and grain-size scales for sediments are included in appendices. Like other modules in the series, this module is inquiry- and problem-oriented, dealing with interdisciplinary, contemporary, and pragmatic aspects of the subject matter. It is designed to be open-ended so that ideas can be incorporated into higher level classwork. (Author/JN)

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Slope Stability

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in Laboratory Experimen

CEGS Programs Publication Number 15

SLOPE STABILITY

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CONTENTS

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FOREWORD

This publication is another in a series of single-topic problem modules intended for use in undergraduate geology and earth science courses. This module is also appropriate for use in undergraduate civil engineering and engineering geology courses. It was prepared under the direction of the Instructional Materials Program (IMP) panel of the Council on Education in the Geological Sciences (CEGS) a project of the American Geological Institute (AGI) supported by the National Science Foundation and is presented through the cooperation of the McGraw-Hill Book Company.

Each module in this series serves as a model from which modern aspects of concepts basic to geology can be introduced. Like other modules in this series, *Slope Stability* is inquiry and problem-oriented and deals with interdisciplinary, contemporary, and pragmatic aspects of its subject matter matter difficult to treat in a more typical textbook fashion. All modules in this series are designed to be open-ended so that ideas from them can be incorporated into higher level class work. They should inspire teachers to develop similar materials in areas of their own interest and competence.

It is intended that all modules be capable of being used alone, either as fully integrated text/manual/laboratory materials or as a supplementary resource to other course materials. Therefore, they are designed to be self contained, and their written parts are arranged in a manner that can be adapted to special local needs or conditions. Some are essentially a single laboratory exercise, others might occupy nearly an entire semester to complete satisfactorily. Their breadth is as variable as their depth.

Slope Stability is intended to give students broad insight into a host of mass-movement phenomena and related natural features, whether influenced by human activities or not. The apparatus and text all available from the publisher together are a springboard from which many other useful investigations may be launched. Some users may have their own visual aids to accompany the text and illustrate problems. A few may prefer to build their own apparatus, which may, but need not, be similar in design to that available commercially from the publisher.

Early in 1967 while he was director of CEGS, John W. Harbaugh introduced the idea of presenting a module series. Raymond Pestrong, experienced in geomorphologic research in California and Louisiana, where he could observe many of the features and phenomena about which this text is concerned, was responsive to the suggestion that a mass-movement module be developed. In its various versions each iteration a large improvement over its predecessor–the module was tested by about 200 students.

As author, Raymond Pestrong deserves a hero's medal for his willingness to accept criticisms and suggestions. Feedback to him from the editors was based in large measure on the many student and faculty comments received.

Among the geologists and students who were especially helpful in their reviews of the materials are John W. Harbaugh (Stanford University), David Cummings (Occidental College), Jackson E. Lewis (CEGS), F. D. Holland, Jr. (University of North Dakota), and David Ribeca and Robin Salo (Governors State University). Several other faculty members at institutions around the country have had an opportunity to review earlier versions of the module. Its long gestation (the first version was tested in 1968) attests to the module's evolution–always based on prior evaluation.

John DeRoy and, later, Richard J. Sederstrom worked with Hickok Teaching Systems to help develop the necessary apparatus for commercial distribution. Martin A. Torre of the AGI staff photographed the

apparatus. Other photographs are by the author Permission was received from the National Academy of Sciences Highway Research Board to reproduce parts of plate 1 (in Varnes, 1958) as Figures 10 to 14, and Table 1. CEGS and AGI support staff who assisted in the manuscript typing are Elizabeth A. Bennett, Marilyn M. Lerette, Diedre J. McKenzie, and Jane F. Paritzky. The careful eye of Jackson E Lewis greatly simplified our task during the end-stage processing of the module.

Our appreciation is extended to all the above for their contributions to this work.

Peter Fenner
Governors State University
George R. Rapp, Jr.
University of Minnesota

PREFACE

This module is a self standing introduction to studies of slope stability. It has been designed to supplement standard introductory geology laboratory exercises as the need or the interest arises. Because of the very practical applications of the subject, the module should interest students who can see little relevance in the more traditional aspects of the standard introductory laboratories, it will probably interest *most* those who perceive most clearly the need for its study, so *relevance* should be stressed as an especially significant attribute of the subject. It is hoped that environmental geology courses also will be developed wherein this module will be appropriate.

My intent has been to present a self-contained package of text, problem, and laboratory materials that is sufficiently flexible to satisfy the needs of widely varied classroom and instructional situations. The background reading material may be minimized if the module is used in conjunction with a textbook presenting the same information, however, in keeping with CEGS's modular concept it has been included for use especially in a course or individualized study program without a suitable textbook. The quantitative and descriptive problems may be done individually or with the accompanying laboratory experiments. many of the problems may be done at home after some preparatory reading, but the experiments require use of the equipment described briefly in Appendix A and in greater detail where appropriate in the text. Before attempting the experiments, students should consult Appendix A to identify the components provided in the equipment package as well as additional materials that are not supplied.

When the module is used in an introductory geology laboratory, individual problems that appear to best satisfy the needs of a particular class should be selected or modified by the instructor. Bear in mind, though, that the module is not meant to be completed in a single laboratory period. Additionally, case histories of landslides that have occurred nearby should be used as much as possible, and field trips, where feasible, will increase greatly the breadth of experience and understanding.

As one progresses through the module, the following important questions should be kept in mind.

1. What forces cause landslides?
2. What factors control their variety of form and mode of development?
3. What are the different kinds of landslides, and how can we recognize them?
4. How can we determine whether a slope is unstable?
5. What can we do to correct an unstable-slope situation?
6. How are human activities presently affecting the stability of slopes in areas undergoing development?

Raymond Pestrong

INTRODUCTION

The Vaiont Dam in the Italian Alps was to be an engineering marvel a masterpiece in concrete and steel. And indeed it was. When completed in 1959, it was the highest and certainly one of the most beautiful of the thin-arch dams in the world. Rising 266 meters above the deeply incised canyon of the Vaiont River, this graceful structure backed up waters for 6 kilometers, creating a reservoir of impressive dimensions in a deceptively peaceful setting.

On October 9, 1963, the serenity of this alpine scene was shattered when 240 million cubic meters of rock suddenly slipped as much as 600 meters down the southern side of the canyon, displacing a great mass of air, rocks, and water, which rose more than 260 meters up the opposite canyon wall. Within 60 seconds, sufficient debris had fallen into the reservoir to raise its level 150 meters. Subsequent waves of water, rising as high as 100 meters above the top of the dam, destroyed everything in their path for miles downstream. Preceding the water, a tremendous blast of air knocked over trees and small structures, serving as an eerie warning of the watery devastation to follow.

Remarkably, the dam itself, a superbly engineered structure, withstood the onslaught with minor damage, a fact of insignificant consequence to those who suffered downstream. The enormous landslide resulted in the worst dam disaster in history, claiming more than 2600 lives and setting up earth tremors that were recorded as far away as Brussels, a distance of more than 600 kilometers.

The glamour surrounding the construction of this technological showpiece was indeed short-lived. Subsequent litigation dragged on for years, and the reservoir has never again been filled to its intended level. Saddest of all, however, is the fact that the geologic conditions at the site were such that a major landslide could have been predicted. The rocks comprise a thick sequence of limestones with clayey interbeds that had been deformed by mountain-building forces and was later scoured by glaciers. When the glaciers receded, the rapid unloading allowed the rocks to expand which, in turn, caused them to fracture in a zone roughly parallel to the walls of the present canyon. These fractures became enlarged as the Vaiont River cut downward to expose, ultimately, a weak zone of highly fractured and layered rock dipping gently into the canyon walls.

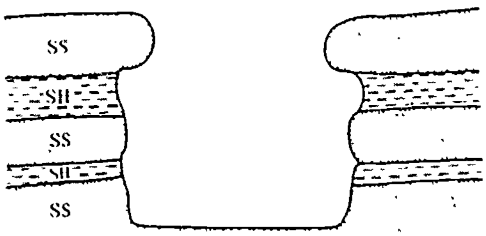
In prehistoric time, a large landslide occurred within the inner valley of the reservoir, distorting the rocks throughout the uppermost section of the 1963 slide area. In 1960, a slide of 700,000 cubic meters occurred along the southern bank of the reservoir, this was accompanied by creep, which set up a pattern of cracks that eventually delineated the approximate limits of the 1963 slide. After the reservoir began to fill in 1960, the cohesive forces within the rocks were weakened by the buoyant force of the water, and slow downslope movements were initiated. These movements, increasing to more than 40 centimeters per day, were noted by late September 1963, but by the time remedial action was taken, it was too late, and at 10:41 P.M. on October 9 the disaster occurred.

It is a tragic fact, reflected elsewhere on numerous occasions throughout history, that in restrospect, those in charge recognize that calamities could have been prevented. The geologic evidence at the Vaiont site was present, but it was neither investigated nor heeded. In this instance, the engineers were clearly equal to the task, but unfortunately the task was not outlined–a job that should have been the geologists'.

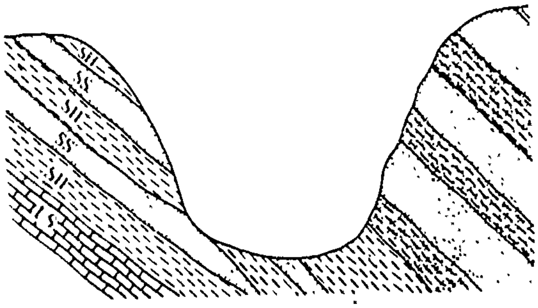
Occurrences such as the Vaiont landslide have been taking place throughout recorded history and are shown in the rock record for prehistoric times. These massive movers of earth materials are among the most spectacular of natural processes, both because of the rapidity with which they occur and because of the great volumes of material often involved. While certainly the most impressive of downslope movements, they represent but one extreme in the continuum of slope-forming processes. In the most common instances, soils formed on the surface of the earth by the weathering of rocks are eroded and redistributed by some transporting medium such as wind, water, or ice. In this module, we will not be concerned with those materials carried by a transporting medium; rather we will consider only those materials moved downslope under the direct influence of gravity. This movement may involve either single discrete particles or aggregates of material, and it is termed *mass wasting.*

When mass wasting involves only consolidated bedrock, the underlying natural controls are purely geologic and involve lithologic or structural factors. An example of a lithologic control is the sliding of a massive sandstone layer over a thin, moist bed of clay. Structural controls, on the other hand, include failures along joint or fault planes or along other zones of structural weakness. Problem 1 illustrates diagrammatically examples of slopes cut into bedrock–slopes of types that abound in nature and are subject to failure for lithologic and structural reasons.

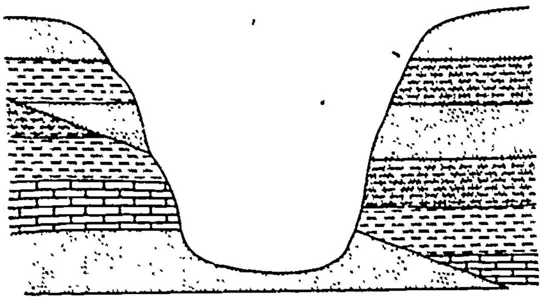
a Alternating horizontal layers of rocks with different degrees of resistance to erosion



b Tilted strata inclined on one side toward the road cut



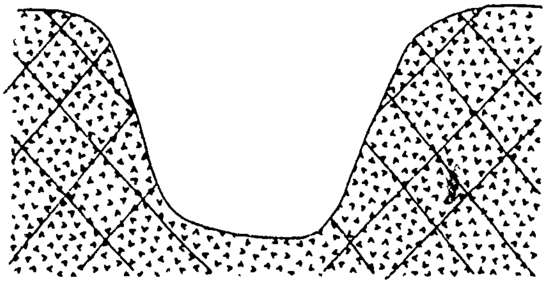
c Horizontal beds cut by a fault inclined toward one side of the road cut



Problem 1

The cross sections below are of slopes composed of consolidated bedrock in a variety of structural and lithologic settings. On each cross section, show how the slopes might fail, and then redraw the cross section in the space to the right of each diagram, showing how the slopes might have been cut to prevent failure.

d Fractures in igneous rock



In which of the examples would failure probably be restricted to just one side of the road cut?

a *b* *c* *d*

Explain the geologic (structural or lithologic) factors most likely responsible for the failure in each example.

a

b

c

d

Although other geologic factors might influence some slides in unconsolidated sediments or soils, the major controls usually involve soil-strength parameters. A failure in a slope composed of uniform soils, for example, might occur after a rainstorm if clays in the soil absorbed a great deal of moisture, thereby adding weight to the slope and reducing the strength of its earth materials. Figure 1 shows that, while rock slope failures generally occur along well-defined planar features related to some form of bedding or jointing, failure surfaces of soil slopes are usually arcuate in profile.

Rock slope

Soil slope

FIG. 1 Examples of typical failures in rock and soil slopes.

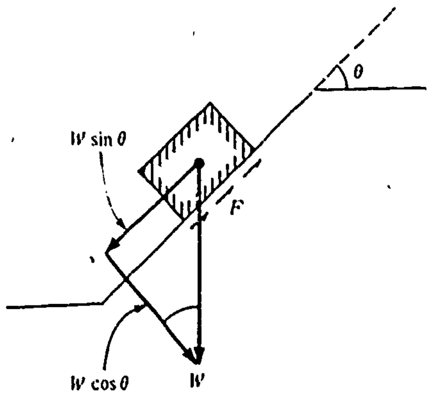
FORCES AT WORK

Any elevated object at rest (whether soil, rock, or man-made) possesses a potential to move downward to a lower level. The source of *energy* necessary to provide the *force* to move that body down a slope is gravity, which is universally present. The magnitude of this *gravitational force* is a function of the masses of the bodies of material involved and the distance between them.

Whether or not a large rock resting near the top of a slope actually moves downward is determined largely by the relative magnitudes of (1) the forces tending to initiate downslope motion (gravity acting on its mass), and (2) the forces tending to oppose this motion (the force of *friction* between the rock and the surface on which it is resting).

The force of gravity, the driving force behind all mass movements, is always directed toward the center of the earth—the focus of the greatest concentration of terrestrial mass. Components of gravity, however, act along any inclined surface in such a way that the steeper the inclination, the greater the component of force tending to initiate movement down the slope; thus, objects move down steeper slopes more readily than down gentler ones. Figure 2 demonstrates the force relationships involved when an object, in this case a block, rests on an inclined surface.

Because the block in Figure 2 can move farther downslope, it has *gravitational potential energy*—a measure of the work it might do if it moved. Were such movement initiated, the potential energy would be converted to energy of motion, *kinetic energy*. If the block does move, when it comes to rest at a lower elevation, it will have lost its kinetic energy and will have a new, but lower, value of potential energy,



θ = slope angle
W = weight of block
$W \cos\theta$ = component of weight pushing into slope
$W \sin\theta$ = component of weight acting down slope
f = coefficient of friction (determined empirically)
F = force of friction (total force resisting motion) $= f(W \cos\theta)$

FIG. 2 Forces acting on a block on an inclined plane. Downward motion of the block occurs when the driving force ($W \sin\theta$) is greater than the resisting force $[F = f(W \cos\theta)]$.

thereby having attained a position much closer to its lowest possible energy level a condition of greater stability.

The basic laws of friction for dry surfaces indicate that the maximum frictional force that can be developed is (1) proportional to that component of the weight pushing into the slope, and (2) independent of the contact area.

Referring to the table of trigonometric functions and to Figure 2, determine the following:

Table of Trigonometric Functions

Slope angle	Sin	Cos	Tan
0°	0.000	1.000	0.000
30°	0.500	0.866	0.577
45°	0.707	0.707	1.000
60°	0.866	0.500	1.732
90°	1.000	1.000	infinity

a As the slope angle increases, what happens to $W \sin \theta$ (the driving force that starts motion)?

b As the slope angle increases, what happens to $W \cos \theta$ (the force pushing into the slope that contributes to resistance to motion)?

c What do you conclude as to the relationship between the gradient of the slope and the tendency to initiate downslope motion?

Laboratory Experiment 1

The optimum arrangement in this and every experiment in this module is for two or three students to work together with each set of equipment and materials.

Equipment

Inclined-plane apparatus
Sandstone block
Protractor
Lead weight
Plastic squeeze bottle
Plastic pan (optional)

Procedure

Assemble the inclined-plane apparatus (Fig. 3), tacking the sheet of fine sandpaper (120 grit) to one side of the first board, leaving the smooth surface of the other side free; on the second board tack the sheet of "clay" paper (600 grit) to one side and the sheet of coarse sandpaper (36 grit) to the other. (Because the final steps in this experiment involve the use of water, it may be advisable to install the apparatus in a plastic pan to prevent water damage to unprotected underlying surfaces.)

a With the sandstone block resting on its largest side at the top of the board bearing the "clay" sandpaper (600 grit), raise the top of the board against the vertical member of the base, increasing the slope gradient by small increments until the block slides all the way down the slope. Measure the slope angle with the protractor, and note the value. Repeat the procedure, note the second value, and then determine the average slope angle necessary to initiate and maintain downslope motion. Under "Surface, Clay" on line 1 of the data sheet that follows, enter the values you measured and calculated in the appropriate boxes ("Run 1," "Run 2," and "Average").

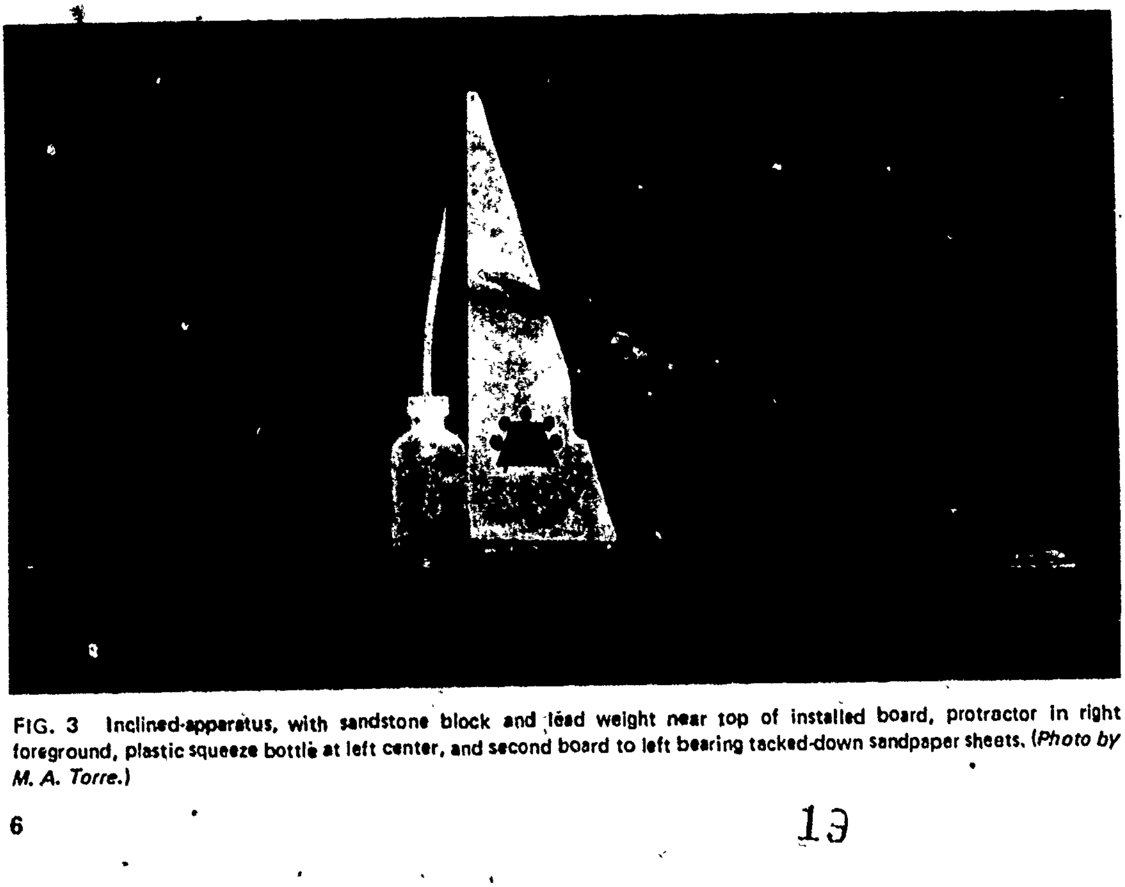


FIG. 3 Inclined-apparatus, with sandstone block and lead weight near top of installed board, protractor in right foreground, plastic squeeze bottle at left center, and second board to left bearing tacked-down sandpaper sheets. (*Photo by M. A. Torre.*)

b Repeat step *a*, but place the sandstone block on the fine sandpaper (120 grit). Enter the values under "Surface, Fine Sand" on line 1 of the data sheet.

c Repeat step *a*, but place the sandstone block on the coarse sandpaper (36 grit). Enter the values under "Surface, Coarse Sand" on line 1 of the data sheet.

d Repeat steps *a* to *c* with the block resting on its smallest side, and enter the values on line 3 of the data sheet.

e Repeat steps *a* to *d* with the lead weight added to the blocks, and enter the values on lines 2 and 4 of the data sheet.

f Repeat steps *a* to *e*, but first wet the sandpaper surfaces with water from the plastic squeeze bottle. Enter the values in the appropriate boxes on lines 5 to 8 of the data sheet.

Experiment 1 Data Sheet Slope angles required to initiate downslope movement

MATERIALS AND CONDITIONS		SURFACE								
		Clay			Fine Sand (Slope angle, degrees)			Coarse Sand		
		Run 1	Run 2	Average	Run 1	Run 2	Average	Run 1	Run 2	Average
DRY	Sandstone block (large surface) [1]									
	[1] with weight									
	Sandstone block (small surface) [2]									
	[2] with weight									
WET	Sandstone block (large surface) [1]									
	[1] with weight									
	Sandstone block (small surface) [2]									
	[2] with weight									

Why are different slope angles necessary to initiate motion of the same block (with the same orientation) on the three different surfaces?

What do you conclude concerning the role of the following factors in initiating motion of a block on an inclined plane?

a Slope material

b Area of contact surface

c Weight of the block

d Moisture

Laboratory Experiment 2

Equipment

- Inclined-plane apparatus
- Two beverage cans
- Plastic measuring cup
- Protractor
- Plastic pan

Procedure

Place two empty beverage cans—one with holes in its bottom, the other without—beside one another on the smooth (unpapered) inclined-plane surface. Then fill both cans with water from the plastic measuring cup, and increase the slope of the inclined plane until one can moves, then the other. (To prevent water damage to unprotected surfaces, it may be advisable to install the apparatus in a plastic pan.)

At what gradient did the can with the perforations begin to move?

At what gradient did the other can begin to move?

Account for any difference in the gradients required to cause both cans to move.

List naturally occurring geologic conditions where this effect might be significant.

a

b

c

Slopes may become overly steep and unstable through a variety of natural and man-made processes (such as undercutting of the base of a slope by a stream and bulldozing away the toe of a slope). Stability is achieved naturally when the slope materials have adjusted to a condition of lower gravitational potential energy. However, this adjustment may involve some form of landsliding, and when it occurs near man-made structures, it may become costly and hazardous. The goal, then, is to find and correct the slope instability before the slope fails. (The subject of landslide control and correction will be discussed in detail later in this module.)

NATURE OF THE MATERIALS

Thus far we have dealt solely with movement of an isolated rock down a slope. However, most surficial materials are combinations of rock and soil and involve strength considerations that are a function of the interaction of these materials and water. The amount of water present is often the most important single factor affecting slope instability.

Although gravity influences all particles equally, the resistance to landsliding mobilized by soil and rocks differs. In this section we will deal with the factors affecting the strength of soil particles and demonstrate the role these play in resisting slope failure. Although soil and sediment may be differentiated readily on the basis of their origin, they may exhibit similar physical properties. For this discussion, soil may be regarded as an organically rich, fine-grained, poorly sorted sediment.

All soil, sediment, and soil and rock combinations owe their strength to frictional and cohesive forces. Furthermore, a simple, fundamental distinction may be made between two major groups of soil or sediment based on these properties. Fine-grained sediments (fine silts and clays) possess *cohesion* the ability of individual particles to attract and stick to one another. This important property is the result of electrostatic forces acting between the individual particles. These forces are the result of the attraction between the particles due to their electric charge and are effective with only the finest sediments.

Sediments coarser than clays and fine silts are relatively unaffected by electrostatic forces and are termed noncohesive. These materials (coarse silt, sand, and gravel) obtain their strength from the *frictional resistance* developed when individual grains move against one another. All materials have unique friction values, but the total frictional force is also a function of the weight of the overlying sediment forcing the grains together.

Friction values define a rough range of slopes that materials of similar size, shape, and composition will form if allowed to fall freely through the air upon one another. The inclination of the steepest slope any given material can maintain naturally is known as the *angle of repose* of that material For most materials, the angle lies between 25 and 40° and depends primarily on the angularity and sorting of the constituent particles. As would be expected, the more angular materials interlock readily to form steeper slopes, also, if the materials are poorly sorted, the fine particles fit among the coarser grains to stabilize the slope. Natural slopes steeper than about 40° are very rare.

Particles moving down a slope steeper than the natural angle of repose for that material have a much

As the roundness or sphericity of particles increases, the angle of repose should ____________

As the angularity of particles increases, the angle of repose should ____________

What effects should the size distribution of the material have on the angle of repose?

Would the slopes maintained by a sediment in air be the same as those formed under water? Explain.

greater chance of reaching the bottom than particles moving down a slope gentler than the angle of repose. It is also more likely that particles are dislodged more easily from steep slopes than from gentle ones.

If loose noncohesive particles do not adhere to each other, how can we explain the vertical walls that children know will stand when they build sand castles at the beach? The answer lies in a special type of cohesive force caused by the *surface tension* of a thin film of water that effectively binds sand-size particles in a partly saturated state (i.e., when both air and water are present in the voids among the sand grains).

Moisture in soil can be present in two forms, as adsorbed films surrounding the grains and as free water occupying part of or all the voids among the grains. If the voids are only partly filled, the moisture is discontinuous (Fig. 4).

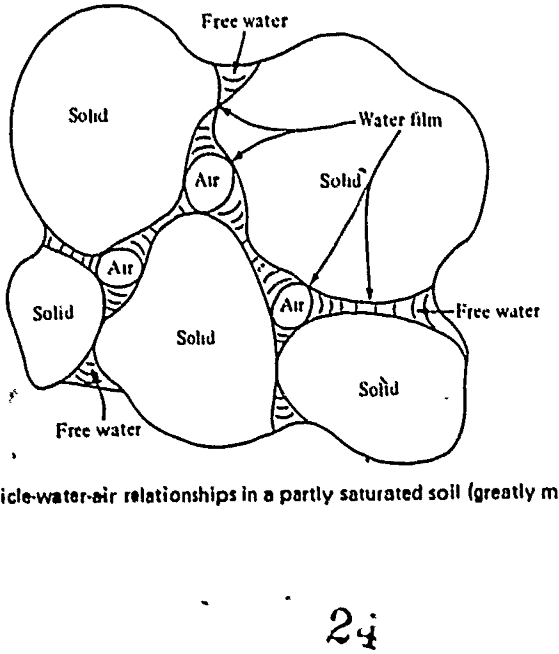


FIG. 4 Particle-water-air relationships in a partly saturated soil (greatly magnified).

The boundary between the air and water in the voids is particularly important. The unbalanced molecular attraction of the water at this boundary gives rise to surface tension, a force acting parallel to the surface of the water in all directions, similar to the tension in a tightly stretched rubber membrane. Surface-tension phenomena explain why a glass of water can be filled so that water extends above the level, or lip, of the container without spilling down the side.

The attraction between water and soil particles causes the water to extend itself along the boundary of the particle and develop a tensile stress. This negative stress in the water produces an attraction between adjacent soil grains, forcing them together. As this stress acts at the air-water interface, it is destroyed on desiccation (drying out) or complete saturation. Partly saturated noncohesive soils often are able to maintain vertical slopes while in this condition, which is called *apparent cohesion.*

Why is apparent cohesion destroyed when a partly saturated soil is desiccated or completely saturated?

As most failures in soil slopes are shear failures (Fig. 5), some discussion of shear strength is appropriate. *Shear strength* is a form of resistance to deformation and is the major structural property of soils. Because of shear strength, earth materials remain in equilibrium when their surfaces are not level, on the other hand, true liquids, which have no shear strength, will in time flatten out and attain equilibrium with a level surface.

Most soils are composed of mixtures of cohesive and noncohesive materials such as clays and sands, respectively. Soil strength is derived from the *cohesive* qualities of the clays and the *frictional* resistance of the sands. The equation for the shear strength of soils, therefore, contains both these physical properties as fundamental parameters:

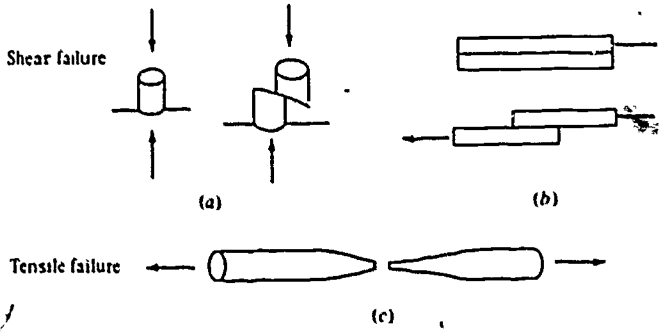


FIG. 5 Shear and tensile failures of natural materials. Shear failures are generally the result of (a) compression or (*b*) two forces not in line, acting opposite one another so that one body slides over the other. (c) In tensile failure, the two forces act along the same line but in opposite directions.

$S = C + \tan \phi$

where S = shear strength
C = cohesion
σ = overlying load
ϕ = friction angle, representing frictional resistance to sliding

Although the value of cohesion is unaffected by the overlying load, the frictional resistance to sliding is directly related to this force and will increase as the load increases.

For a pure clay with high values of cohesion and a theoretical friction angle of zero, the shear-strength equation may be modified to ____________________________________.

For a pure noncohesive sand with a high friction angle, the shear-strength equation may be modified to

____.

Laboratory Experiment 3

Materials of single and mixed grain sizes will be used in this and subsequent experiments. Presented in Appendix B is a summary of the generally recognized size limits of sedimentary particles, the names applied to the particles, and the scales used to measure them.

Equipment

Landslide box
One-foot grooved plastic ruler
Clay
Fine sand
Piston corer
Shear-strength testing apparatus
One-thousand-milliliter graduated cylinder
Red rubber hose and clamp
Sieves (optional)

Procedure

a Assemble the landslide box (Fig. 6) with the three solid rubber stoppers inserted into its bottom from below. In the box prepare a 10-centimeter-high mixture of partly saturated fine sand and clay having the consistency of a stiff, viscous paste. (This mixture should be prepared at least 2 hours before the experiment is to be run and should remain undisturbed for that period of time. After the experiment is completed, the mixture should be dried, preferably in a drying oven if one is available, and may be either stored as a mixture for use by others or sieved and the components returned to their respective containers.)

b After attaching securely the rectangular wooden base of the shear-strength testing apparatus to a table with the C clamp (Fig. 7), obtain a core sample of the mud from the landslide box by using the piston corer (Fig. 6) as follows: With the piston flush with the lip of the corer tube, position the corer vertically on the surface of the mud. Holding the piston in place on the surface, force the corer tube down past it as far as it will go. Withdraw the entire corer from the sediment, and carefully extrude the core onto the wooden base of the shear-strength testing apparatus midway between, and in line with, the two holes. Then, measure the inside diameter d of the corer, and determine the cross-sectional area A of the core according to the relationship

FIG. 6 Landslide box, with back wall to left and front wall to right. Movable wall, handle, and wall pin are installed inside box; three solid rubber stoppers are inserted into bottom of box; and plastic syringe is clamped to back wall. The slotted block, accommodating ruler in later experiments, lies behind syringe. Note that syringe is connected by tubing to single-hole stopper resting on gauze filter. To right of landslide box is piston corer, in front of box are plastic ruler and steel ball. (*Photo by M. A. Torre.*)

$$A = \left(\frac{d}{2}\right)^2 \pi$$

c Measure the original height of the core, and record this value and that of its cross-sectional area in the appropriate spaces on the Experiment 3 Data Sheet; also draw the shape of the core in the space provided. Place the trapezoidal Plexiglas (upper) plate of the load applicator on the core, and attach with cotter pins the 5/16-inch dowels at their tops to the plate and at their bottoms to the similar Plexiglas plate affixed to the top of the plastic jar. Then, fill the graduated cylinder with 1000 milliliters of water, and place one end of the rubber hose near the bottom of the inside of the cylinder, allowing it to curve gently out of the top of the cylinder. Tape the hose loosely to the outside of the cylinder near its top, and attach the clamp to the hose several inches below the tape (to regulate the flow of water). Finally, insert the loose end of the hose into the plastic jar through the hole in its top, and start the flow of water into the jar, adjusting the rate of flow to about 250 milliliters per minute.

d Note the *load* (the volume of water removed from the graduated cylinder) and the *deformation* (the decreased height of the core), and record these figures on the data sheet; deformation readings should be made roughly every 25 milliliters, the frequency depending on the stiffness of the sediment (which controls its rate of failure). Continue this procedure until failure occurs or until the core is shortened by at least 20 percent of its original height.

e Measure and record on the data sheet the final height of the sediment core when it fails. Draw the shape of the core in the appropriate space, paying special attention to the angle of the failure plane. Describe the failure of the core. (That is, did moisture beads pour from the mud's interior? Were there any tension cracks? What was their orientation? Did the rate of deformation vary?)

f Plot the load and deformation data on the graph that follows the data sheet. From this *load-deformation curve*, one can determine the shear strength of the mud (in grams per square centimeter, g/cm^2) according to this relationship:

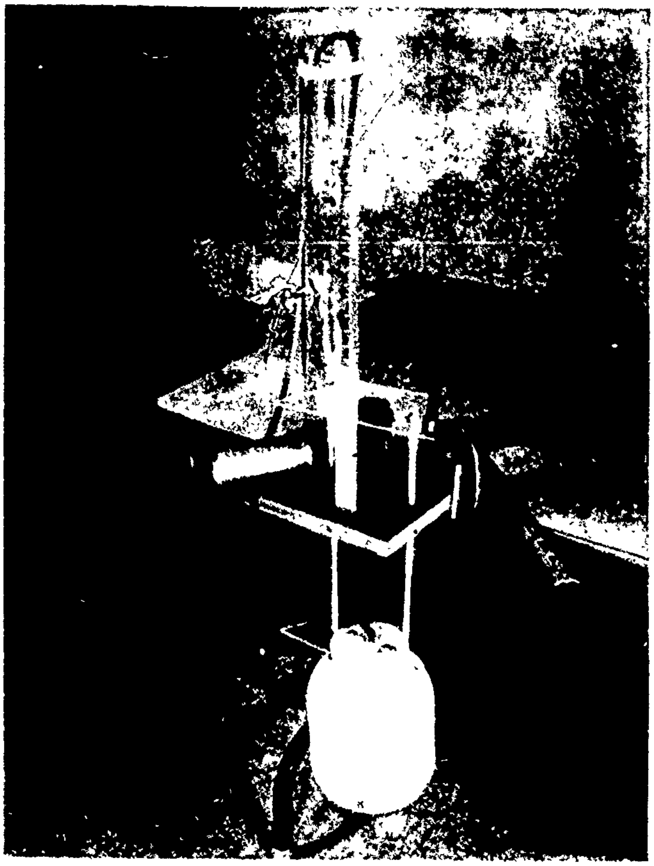


FIG. 7 Shear-strength testing apparatus attached with C clamp to table. Note corer resting on rectangular shaped base and core sample between top of base and free trapezoidal Plexiglas plate, plate is part of load applicator and is connected with cotter-pinned small dowels to second Plexiglas plate attached to screw top of plastic jar. The load, water, flows from graduated cylinder through rubber tubing into plastic jar. (*Photo by Hickok.*)

$$\text{Shear strength} = \frac{1}{2}\ \frac{\text{failure load, g}}{\text{original cross-sectional area of the core, cm}^2}$$

(When failure does not occur, use the load at 20 percent deformation as the failure load.)

g The *angle of internal friction* of the sediment may be approximated by the relationship $\theta = 90$ 2α, where θ is the angle of internal friction and α is the angle between the failure plane and the horizontal.

As the friction angle for the sediment increases, what should happen to the angle between the failure plane and the horizontal?

The test you have just conducted is called an *unconfined compressive strength test.* Why was the core able to stand by itself, unconfined, in the testing device?

Experiment 3 Data Sheet   Shear strength of mud core

Initial height of core, cm ______
less
Final height of core, cm ______
equals
Amount of deformation, cm ______

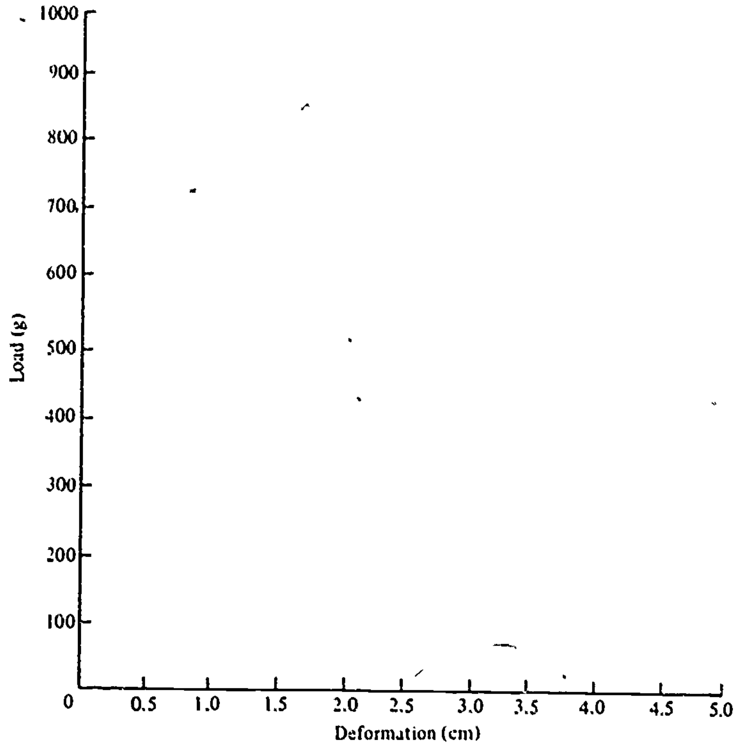
Original cross-sectional area of core, cm^2 ______

LOAD*, g		DEFORMATION, cm		SHAPE OF CORE	
Volume	Weight	Per load reading	Cumulative	Before failure	After failure
				DESCRIPTION OF FAILURE	

---

*For experimental purposes, 1 milliliter (ml) equals 1 cubic centimeter (cc) of water and weighs 1 gram (g)

Experiment 3: Load-deformation curve



From the experimental data, determine the following:

a Load at failure (or at 20 percent deformation)

b Shear strength $= \frac{1}{2} \frac{\text{failure load, g}}{\text{cross-sectional area, cm}^2}$

c Angle of internal friction $\theta = 90 - 2\alpha$

Just how does water play its important role in affecting slope instability? On soil slopes its role as a lubricant is much less than one might expect. With quartz grains, for example, water actually increases the frictional force and acts as an antilubricant. On the other hand, it has already been pointed out how complete saturation destroys the condition of apparent cohesion in partly saturated materials and, therefore, decreases the strength of these materials. In addition, many clays have the capacity to absorb great quantities of water, thereby expanding and increasing in weight; the moisture increases the separation between the clay particles which, in turn, reduces the electrostatic effects responsible for cohesion; the net result, besides the increased weight, is to decrease the consistency of the clays (i.e., make them more watery) and to reduce significantly their shear strength.

Other natural hazards that increase the likelihood of slope failures include earthquakes and forest fires. Earthquakes often act as a triggering mechanism for large landslides, especially where the slopes contain highly fractured rock or certain clays that lose much of their strength when suddenly stressed (Figs. 8 and 9). Forest fires aid mass wasting by removing the natural cover that protects the slopes from

FIG. 8 Author inspecting landslide on old Highway 1 (Coast Highway), south of San Francisco. An earthquake along the San Andreas fault triggered this failure; its magnitude was 5.5, and its epicenter nearby.

FIG. 9 Part of old Highway 1 removed during a 1957 slide. Location of this view is 1 mile south of that shown in Figure 8. Depression on the horizon is the main trace of the San Andreas fault at Bolinas Lagoon.

extensive erosion during heavy rains. Mudflows often follow when an area hit hard by forest fires in the dry summer months is exposed to a very wet winter. The Los Angeles area is one in which this destructive chain of events often repeats itself.

Thus, it should be expected that most mass movements would occur after protracted rainfall, when the soil becomes saturated, its strength reduced, and its weight increased.

Problem 2

In outline form, develop a sequence of events to illustrate how each of the following natural factors could be effective in initiating a landslide.

Heavy rainfall

a

b

c

d

e

Earthquake

a

b

c

d

e

•

•

•

Stream erosion

a

b

c

d

e

•

•

•

Forest fire

a

b

c

d

e

•

•

•

What other natural factors might also be effective in initiating landslides?

What works of man might be similarly effective?

NATURE OF THE MOVEMENT

The general term *landslide* is misleading because it implies sliding, whereas the types of movement associated with mass wasting are varied—ranging from imperceptibly slow downslope creep of surface soils to extremely rapid falls of rock fragments through the air. Inherent in this variation is *speed of movement*, and in Figure 10 terms used to describe rates of movement are equated with two scales of numerical velocity values.

Like the creep and falls already mentioned, slides, flows, and combinations thereof are specific types of movement, and their principal attributes may be described as follows:

> *Falls* are extremely common and generally involve discrete units of rock or consolidated soil moving through the air with little or no interaction among the moving units (Fig. 11) Velocities are very high, and although the falls may be preceded by minor movements of the rocks, they generally occur quite suddenly. Undercut cliffs are the most common setting for this type of landslide movement.

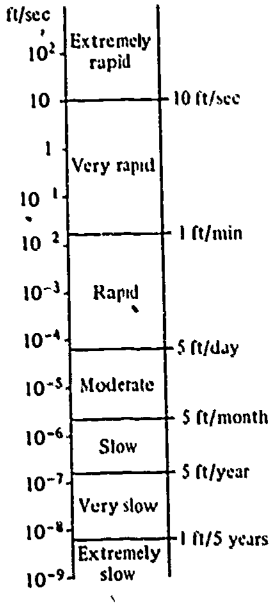


FIG. 10 Approximate ranges of rates of movement. (*From Varnes*, 1958.)

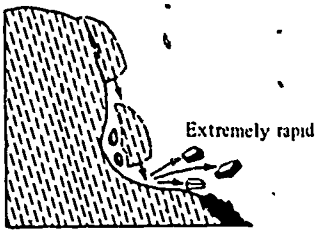
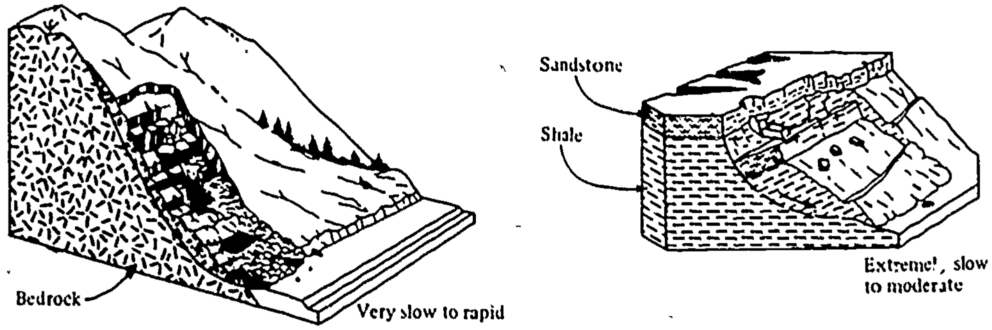


FIG. 11 Diagrammatic cross section of fall (rockfall). *(Modified from Varnes,* 1958.)



(*a*) (*b*)

FIG. 12 Block diagrams of slides. (*a*) Debris slide; (*b*) slump. *(Modified from Varnes,* 1958.)

Slides are more complex and result from shear failure between two or more surfaces originally in contact with one another (Fig. 12). Many types of slide failures are recognized, and they are differentiated by the nature of the movement of the individual units that are sliding. Some large blocks move as a single unit on curved or planar surfaces, others may become mixed together during the movement. The velocity of movement during sliding varies- from very slow to very rapid.

Flows (Fig. 13) are an important type of failure in which the mass being displaced takes the form of a viscous liquid. Flows occur in many dry and wet soils and rock materials. Movement is generally

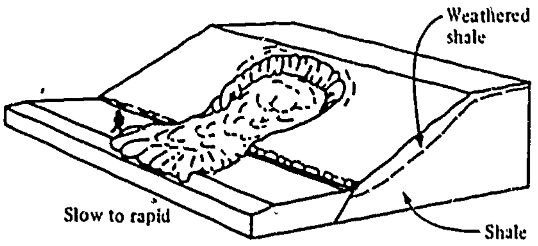


FIG. 13 Block diagram of flow (slow earthflow). Figure at left of foot of flow is author, drawn for scale. *(Modified from Varnes,* 1958.)

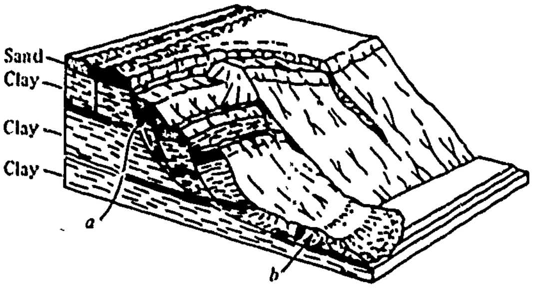


FIG. 14 Block diagram of complex movement. (*a*) Slump; (*b*) earthflow. *(Modified from Varnes,* 1958.)

very rapid, although the velocity is a function of the size and angularity of the particles, the slope gradient, and the moisture content of the materials.

The most common example of mass wasting is one in which a landslide begins with one type of movement and continues with another. Figure 14 illustrates the initial sliding of a large block of poorly consolidated material that turned into a flow at its base. Some clays, termed *sensitive* clays, lose most of their strength when suddenly stressed, and flow like a liquid. If the movement of a large block of such a clay were triggered by an earthquake, a *complex* landslide would result in which the initial movement would be called a slide and the subsequent movement a flow.

MASS-MOVEMENT CLASSIFICATION

Mass movements occur in markedly different soil and rock types and may be of almost every conceivable size and shape. They take place at all elevations and in every climate. This wide range of variables produces many different types of failures, which experts have classified according to factors responsible for their initiation and subsequent development. One of the most useful classifications, summarized in Table 1, was proposed by Varnes in 1958 in a special report of the National Research Council's Highway Research Board.

This arrangement classifies mass movements according to *type of movement* and *type of material* involved in the displacement. The scheme is subdivided further according to moisture-content variation within the unconsolidated material and to the rapidity and nature of movement within the deformed mass

TABLE 1 Abbreviated Classification of Landslides, Modified from Varnes, 1958

TYPE OF MOVEMENT		TYPE OF MATERIAL			
		BEDROCK		SOILS	
FALLS		Rockfall		Soilfall	
SLIDES	Few Units	Rotational Slump	Planar Block Glide	Planar Block Glide	Rotational Block Slump
	Many Units		Rockslide	Debris Slide	Failure by Lateral Spreading
FLOWS		(ALL MATERIALS UNCONSOLIDATED)			
	Dry	Rock Fragments	Sand or Silt	Mixed	Mostly Plastic
		Rock-Fragment Flow	Sand Loess Rapid Flow		
			Rapid Earthflow	Debris Avalanche	Slow Earthflow
	Wet		Sand or Silt Flow	Debris Flow	Mudflow
COMPLEX		Combinations of Any of the Above Materials or Type(s) of Movement			

Note that this classification excludes normal surficial creep, solifluction, rock glaciers, and snow avalanches; these and other movements are described and discussed in depth later in the module.

Laboratory Experiment 4

Equipment

- Landslide box
- One-foot grooved plastic ruler
- Steel ball
- Clay
- Fine sand
- Medium or coarse sand
- Mixture of sand, silt, and clay
- Fine gravel
- Protractor
- Sieves (optional)
- Plastic pan (optional)

Procedure

a With the movable wall of the clean landslide box approximately 8 centimeters from the back wall (Fig. 6), fill the space between these walls with a dry sample of fine gravel to within 3 centimeters of the top of the box. (Keep the wall pin in an appropriate hole in the handle so that the movable wall will remain stationary while you fill the box.)

b Remove the wall pin, and pull the movable wall all the way to the front wall.

c Measure the angle of repose of the material with the protractor, and record the value under "initial slope angle" on Experiment 4 Data Sheet A.

Experiment 4 Data Sheet A Dry sediments

	SEDIMENT TYPE				
	Fine Gravel	Mixture	Medium or Coarse Sand	Fine Sand	Clay
Initial slope angle					
Adjusted slope angle					
Landslide type					
Landslide sketch					

d With the ruler inserted, numbers up, in a slot on the outside of the back wall of the box (see frontispiece), roll the steel ball against the wall 10 times by letting it roll freely down the full length of the ruler until it strikes the wall. (Tapping with a small hammer or other rod is equally effective.)

What natural phenomenon might the striker simulate?

e Note and record the adjusted slope angle in the appropriate place on Data Sheet A.

f Using the classification scheme in Table 1, classify the landslide developed in step *b* above, and in the appropriate spaces on Data Sheet A record the name, and draw a cross-sectional sketch of the slide.

g Pour the gravel into its original container, clean the box, and repeat steps *a* to *f* with the mixture of sand, silt, and clay, the medium or coarse sand, the fine sand, and the clay. In each case record the data where appropriate on Data Sheet A, clean the box after use, and return the sediment to its container. (If not all materials are available, use those at hand, and record your observations in the spaces provided that are most appropriate.)

h Repeat steps *a* to *f* with the fine sand; however, this time *partly saturate* the sediment with water before moving the wall. (The sediment is partly saturated when almost all the voids are filled with water. Make certain that water is *not* standing above the sediment level when you are ready to begin the experiment.) Record your observations in the appropriate spaces on Experiment 4 Data Sheet B. (As in some earlier experiments, it is advisable to install the landslide box in a plastic

Experiment 4 Data Sheet B Partly saturated sediments

	SEDIMENT TYPE		
	Gravel	Coarse Sand	Fine Sand
Initial slope angle			
Description of slope adjustment			
Landslide type			
Landslide sketch			

pan to prevent water damage to unprotected surfaces) *Do not run this test with wet clays as their extreme impermeability and cohesiveness make them difficult to manipulate and the apparatus difficult to clean after use.*

Account for the differences between the initial and adjusted slopes under dry and partly saturated conditions.

i Repack and adjust the partly saturated fine sand as you did for step *h*, however, this time *completely saturate* the sediment so that all the voids are filled with water and water *is* standing above the sediment level at the time you are ready to pull back the movable wall. Repeat steps *a* to *f*, and record your observations on Experiment 4 Data Sheet C. (When finished with the fine sand, dry it, preferably in a drying oven if available, and return it to its container. Also, clean and dry the landslide box.)

Experiment 4 Data Sheet C Saturated sediments

	SEDIMENT TYPE		
	Gravel	Coarse Sand	Fine Sand
Initial slope angle			
Description of slope adjustment			
Landslide type			
Landslide sketch			

4i

j Repeat steps *h* and *i* with the coarse sand, and record your observations where appropriate on Data Sheets B and C.

k Repeat steps *h* and *i* with the gravel, and record your observations where appropriate on Data Sheets B and C.

Describe the differences between the initial and adjusted slopes for the same sediment in the dry, partly saturated, and completely saturated states.

l Arrange in the landslide box separate layers of gravel, coarse sand, and fine sand, and repeat the preceding steps for the stratified sediments under *dry* and *partly saturated* conditions. (After completing this operation, clean and dry the box, and dry, sieve, and return the sediments to their respective containers.)

Describe the effects of stratification on slope failure.

Account for any differences in the slope angles determined for the single blocks in Laboratory Experiment 1 and the angle of repose measured for the unconsolidated material in Laboratory Experiment 4.

LANDSLIDE RECOGNITION

RECENT LANDSLIDES

Once a slope has failed, the surface manifestations of a landslide are very clear. As most slides are essentially surficial and restricted to *regolith* material (i.e., surface soils and rocks above bedrock), a typical landslide scar appears very much like that shown in Fig. 15. The arcuate *scarp* (opening downslope) at the top of the the slide (Fig. 16) and the irregular, hummocky, lobate terrain near its base (Fig. 17) are the most distinctive characteristics of such failures. The lobate form of the debris that has slid becomes more pronounced as the size of the material decreases and as its moisture content increases. Cracks commonly radiate out to the lobate front of the slide mass, and many small slump blocks usually occur near its top. Roughly concentric transverse cracks separate thate small slumps and intersect the radical cracks near their base. Departures from this idealized landslide form increase as geologic controls become more pronounced and the soil becomes less homogeneous.

Owing to disrupted vegetation (Fig. 18), scars on the sides of slopes are often recognizable The form of displacement of slide debris varies considerably. Often, the debris dams rivers, forming a variety of lakes and ponds, in other instances—depending on the volume of material involved large sheets of debris distinctly different from the surfaces on which they rest may mantle an area.

A landslide generally alters the hydrologic regime in its vicinity, and unique or anomalous vegetative associations often result from the change in the ground-water or surface-water conditions. If springs occur within the slide mass, hydrophilic (water-loving) trees and shrubs may be present, outlining the seepage area. The slide may also transport distinctive vegetation intact into areas where it contrasts with quite

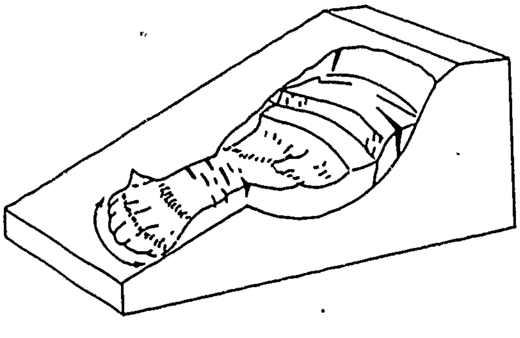


FIG. 15 Block diagram of typical landslide form.

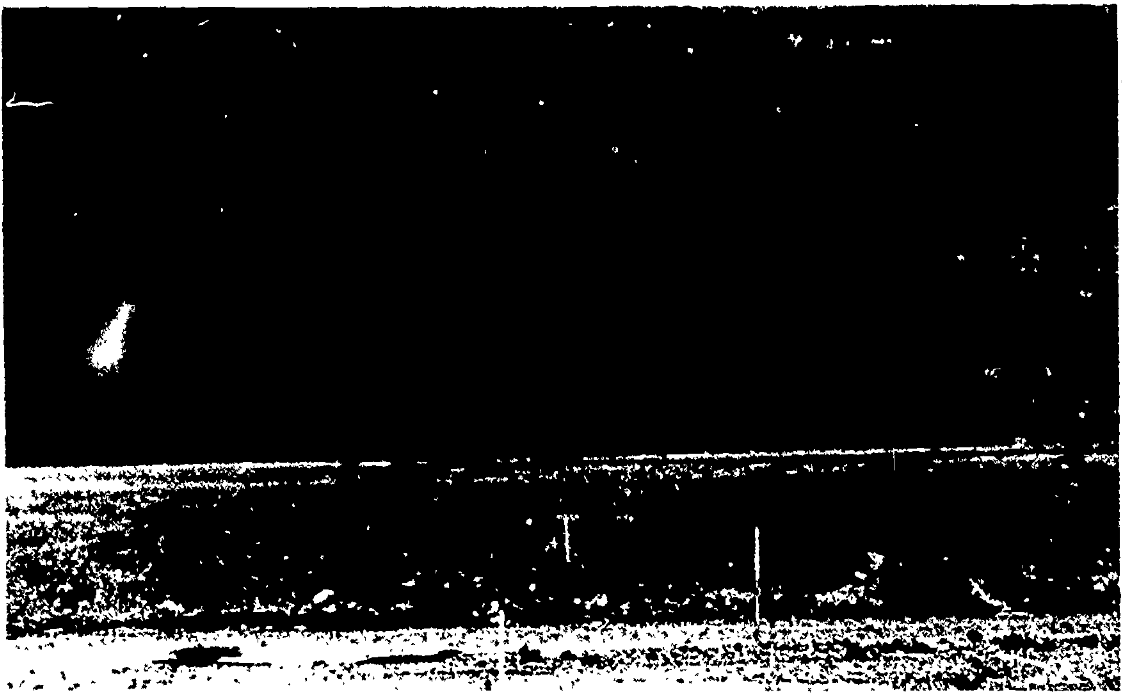


FIG. 16 Arcuate scarp at the top of a slide in a road cut near Woodside, California.

FIG. 17 Hummocky lobate form at the front of a landslide near Pacifica, California.

FIG. 18 Landslide scars near Mussel Rock, south of San Francisco. These slides, triggered by the Daly City earthquake of 1957, closed the Coast Highway. Note the house on the skyline near the edge of the cliff. The main trace of the San Andreas fault runs along the base of the scarp from left to right.

different types of vegetation. Trees distorted by landslide movement are also common (Fig. 19).

Taluses and other rock falls are readily identifiable because of the broken, angular rocks that accumulate at the base of the cliffs (Fig. 20). The similarity between the angular material in the talus and the rock in the cliff clearly indicates the source of the debris. In contrast, stream deposits are better sorted and their particles more rounded because of the abrasion they undergo during transport.

Slide deposits are called *colluvium*. Like glaciers, landslides can transport debris of varied sizes and shapes, but unlike glaciers a landslide rarely displaces material more than several hectometers from its source. Therefore, colluvial deposits are very poorly sorted and can contain material of all sizes–from fine clays to large angular boulders. Organic debris is also commonly mixed with the deposits.

At an excavation for a building site near San Francisco, for example, a piece of partly decayed tree trunk was found beneath 15 meters of consolidated sandstone. It could not have been deposited in a normal manner beneath the sand sequence, as it would have decomposed in far less time than that necessary for the lithification of the sands. A landslide origin was hypothesized, and further study identified a massive prehistoric slide at the proposed development site. With this information, and because nearby homesites had previously suffered severe slide damage, excavation and engineering plans were radically altered.

Colluvial deposits are poorly stratified, and the materials are not well-rounded because they generally do not travel far enough to become significantly abraded. They usually come to rest as a structureless, chaotic jumble of disoriented debris of varied sizes and shapes. Mudflow deposits are sometimes an exception but only if sufficient water is present in the flow to begin to sort and stratify the material. When lithified, colluvial deposits generally form breccias, the specific variety of which depends on the nature of the constituent particles.

INCIPIENT LANDSLIDES

It is important to be able to recognize incipient slope failures. The clues to such slope conditions are generally more than subtle, and ease of recognition may depend on how close a slope is to failing. Features

FIG. 19 Trees distorted by landslide movement.

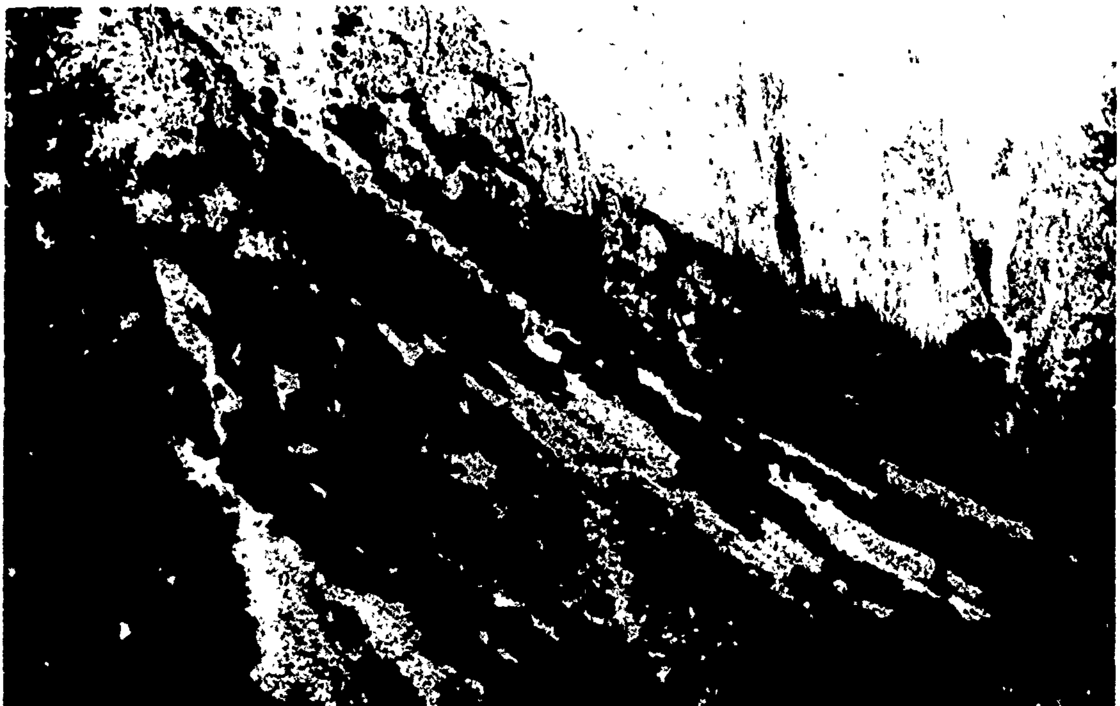


FIG. 20 Talus accumulations at the base of the glacially scoured cliffs in Yosemite Valley. Growing vegetation indicates that the talus is inactive.

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demonstrating surface creep often indicate a slope condition that if left unchecked could result in a major landslide should the region be suddenly stressed, as by an earthquake.

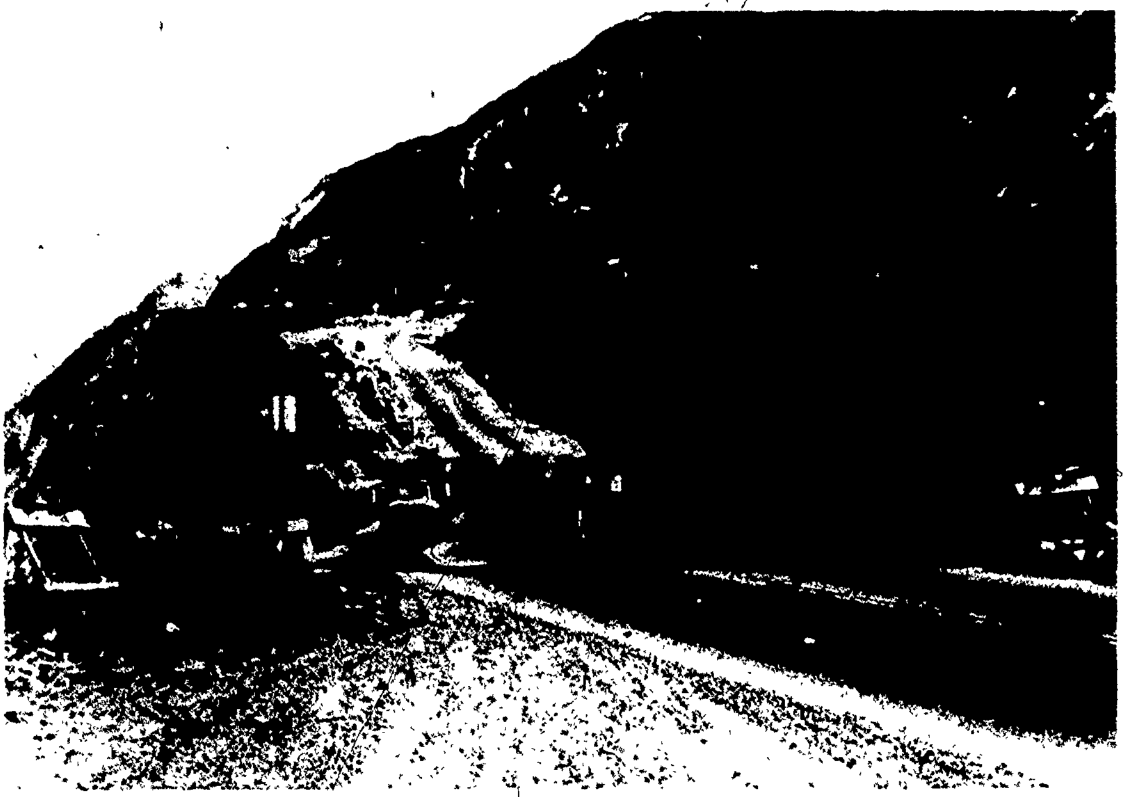
Among the first signs of active slide movement are arcuate cracks, parallel (*en échelon*) lines of cracks, and shrinkage cracks in the surface soil. These are especially significant when they are close to steep cliffs or recent cuts (Fig. 21). Lines of springs and seeps on slopes indicate the presence of permeable materials underlain by impermeable soils or rock and the possible presence of slide-prone conditions. Undercutting of river banks by actively eroding streams, or of coastal cliffs by storm waves, creates more apparent and different potential slide conditions.

Predictions about the stability of slopes can be made readily when pertinent physical properties such as shear strength, expansive clay content, or permeability of surficial soils are known. With solid rocks, however, structural and lithologic conditions control the tendency of slopes to slide, and site investigations by a trained geologist are required to determine the potential landslide hazard. Among the clearest dangers to be looked for are bedding, joint, or fault planes dipping into an exposed cut or slope—situations depicted diagrammatically in Problem 1. Compounding the peril are layers of relatively *incompetent* (i.e., weak) or slippery materials, such as clays, upon which sliding could occur. If these conditions are present in an area where earthquakes are common, an extremely high landslide hazard exists (Fig. 22).

Thus far, we have considered only natural hazards, but many serious landslides occur because of human tampering with the natural environment without completely understanding the consequences. The disaster at Vaiont Dam is a case in point. On a less grandiose but more personal level, an individual homeowner on a hillside site can significantly affect the stability of the slope on which he lives.

A person who goes about increasing the size of his backyard by cutting into the base of the slope behind his house may seriously affect the stability of that slope. By removing material at the base, he is removing the support for part of that slope—material that normally acts as a buttress holding back the material upslope. Another common type of slope failure occurs because of poor drainage—when excess moisture gets onto a slope but cannot readily drain off; if the slope is composed of soil, the weight of the soil is increased while its strength is reduced; and if it is a rock slope, the water may act as a lubricant along joint or bedding planes.

FIG. 21 Cracks and small scarps close to the head of an active mudflow near San Francisco. Note the old paved roadway—long since destroyed.



(a)

(b)

FIG. 22 Two views (a and b) of subsidence at Devils' Slide on the Pacific Coast Highway of San Francisco. Steeply dipping sandstones and shales present a continual slide hazard along this stretch of road. The subsidence shown in the photos occurred during the heavy winter rains of 1968-1969 which often closed the road.

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PREHISTORIC LANDSLIDES

Ancient landslides may be difficult to recognize unless they are of such massive proportions that they dwarf surrounding features. If the slide is not very old, its scars and deposits may still be visible on the surface, but the evidence for most prehistoric landslides lies in the rocks. Lithified colluvial breccias in a discordant attitude with respect to the surrounding rocks are the clearest proof of such ancient activity.

Aerial photographic interpretation provides an important tool in identifying and outlining slide-prone areas. Large-scale low-altitude photos of a large area often are necessary to identify regional slope conditions that are obscured and vague when viewed too closely on the ground. In addition, new procedures in remote sensing, such as side-looking aerial radar (SLAR) and multiband photography, provide techniques for enhancing topographic and vegetative features indicative of landslide conditions.

Although most landslides seem to occur suddenly and without any warning of the impending failure, this may be attributable in part to man's inability to recognize early-warning signals. These may include widening cracks in the soil, small earth slides that precede larger ones, and even warnings by animals. Preceding certain large landslides, animals have been observed rapidly leaving the vicinity, and on other occasions an extreme uneasiness has been noticed among those creatures most intimately in tune with the earth. Perhaps man will someday be able to harness this animal sensitivity to natural hazards and convert it into landslide early-warning systems. Until then, however, we must learn to accurately assess the hazard before we tamper with the land.

STABILITY ANALYSIS

The purpose of a stability analysis is to determine whether a slope is about to fail or is inherently stable. Such a vital analysis involves evaluating the relative magnitudes of the forces tending to oppose failure and those tending to produce it. These forces act differently for rock and for soil slopes, as illustrated in the following examples.

ROCK SLOPES

Stability of rock slopes is primarily a function of the geologic structure and lithologic characteristics of rocks at the site. Failure generally occurs along well-defined planes of lithologic or structural significance (i.e., bedding planes or fracture surfaces), and it starts when the strength of the rock is exceeded by the driving forces tending to initiate downslope movement.

The block diagram in Figure 23 portrays an outcropping sandstone block resting conformably on a thin shale bed, both of which dip eastward at angle θ, the shale bed delineates the most likely plane along which failure might occur. Line AB is a profile of an imaginary slice through a sloping surface. The factor

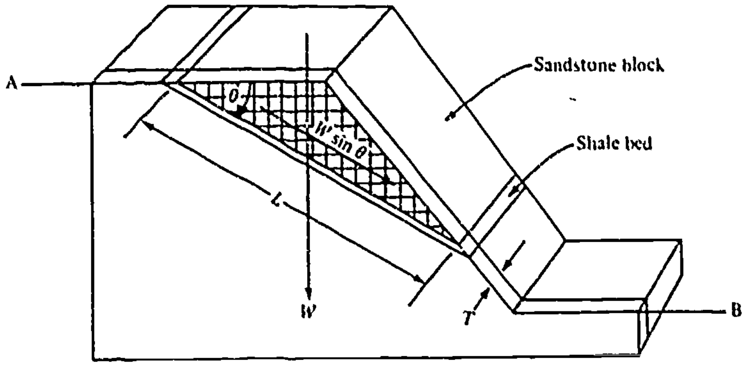


FIG. 23 Factors of rock slope-stability analysis.

safety a measure of the slope's stability -will be calculated for a width, or thickness T, of a slice of the slope.

In Figure 23, the force tending to oppose failure is the shear strength S of the shale bed acting (over a thickness T) along the length L of the contact between the shale and the sandstone layer The force tending to produce movement is that component of the weight of the block W acting down the slope ($W \sin \theta$)

For a given width of slice of thickness T, if S times L is greater than $W \sin \theta$, the slope will not fail, for there will be sufficient strength within the rocks to resist the force of gravity on the mass of the rock (gravity × mass = weight). The ratio between the resisting and driving forces is commonly called the *factor of safety* or *safety factor* (S.F.), this indication of the relative stability of the slope is determined by the equation

$$\text{S.F.} = \frac{\text{sum of opposing forces}}{\text{sum of driving forces}} = \frac{SLT}{W \sin \theta}$$

The slope is stable when the factor of safety is greater than 1. When it is less than 1, failure should occur if it has not already done so. With a factor of safety of 1, failure is impending.

Figure 24 illustrates diagrammatically the factors in a stability analysis for a rock slope where the sliding of a sandstone block over a shale layer is imminent. (The English system of units is used in this example to facilitate ease of comparison with examples in the literature.) The area of the sandstone block is determined by counting the squares in the cross section (53 × 100 square feet per square = 5300 square feet), and the weight of 1 cubic foot of sandstone is given as 135 pounds.

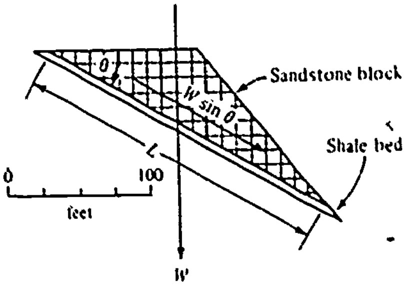


FIG. 24 Stability-analysis cross section of rock slope. $S = 1000 \text{ lb/ft}^2$ (given). $L = 220$ ft (scaled from cross section). $\theta = 30°$ (scaled from cross section). $W =$ (area [5300 ft^2] × thickness [1 ft] × density [135 lb/ft^3]) = 715,500 lb.

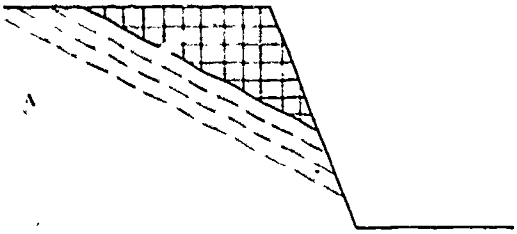
For this particular example, assuming a 1-foot-thick slice is being analyzed, the safety factor

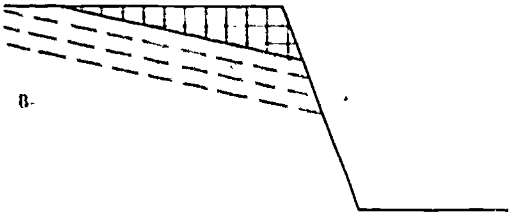
$$\text{S.F.} = \frac{SLT}{W \sin \theta} = \frac{1000 \text{ lb/ft}^2 \times 220 \text{ ft} \times 1 \text{ ft}}{715{,}500 \text{ lb} \times 0.5} = \frac{220{,}000}{357{,}750} = 0.616$$

Because the safety factor is less than 1, the slope is unstable and should fail.

Problem 3

Following the procedures employed in the above example, determine the safety factors (and, therefore, the relative stabilities) for the slopes depicted below. Use the same values as those given previously for scale, shear strength, and rock weight.





S.F. $= \frac{SLT}{W \sin \theta} =$

S.F. $= \frac{SLT}{W \sin \theta} =$

Stability:

Stability:

SOIL SLOPES

Slope failures in homogeneous soils differ from those in rock in that the surface of failure (slip surface) is generally arcuate in shape and not related to any specific structural or lithologic boundary.

The analysis again involves the determination of those forces tending to initiate and those tending to resist the landslide. However, because the impending movement has a circular form and would cause rotation of the soil mass, a different method of analysis, *moment analysis*, is employed. With this method, one calculates the tendency of a force to turn or rotate a body about an axis. The moment (or measure of the magnitude) of a force about the center of the failure circle (which determined experimentally) is obtained by multiplying the force magnitude times the perpendicular distance from the force to the center of the circle.

As illustrated in Figure 25, for a given thickness T, the moment tending to initiate movement equals the weight of the slide mass W (acting through the center of gravity of the mass) times the perpendicular distance D between W and the center of the failure circle.

The moment tending to resist movement, for a slice of thickness T, equals the available shear strength S of the soil times the length L of the circular arc over which it is acting times its perpendicular distance R from the center of the failure circle.

The factor of safety, then, is equal to the resisting moment divided by the initiating moment. Relative to the elements in Figure 25, the safety factor

$$\text{S.F.} = \frac{SLRT}{WD}$$

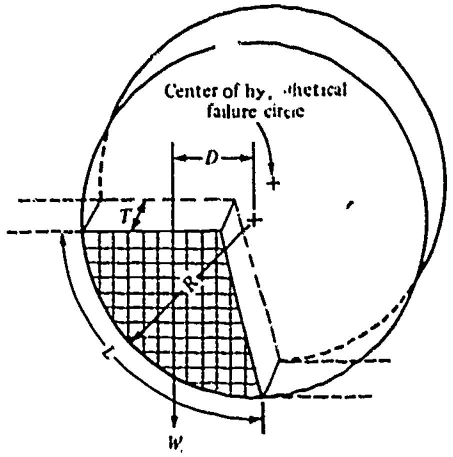


FIG. 25 Factors of soil slope-stability analysis.

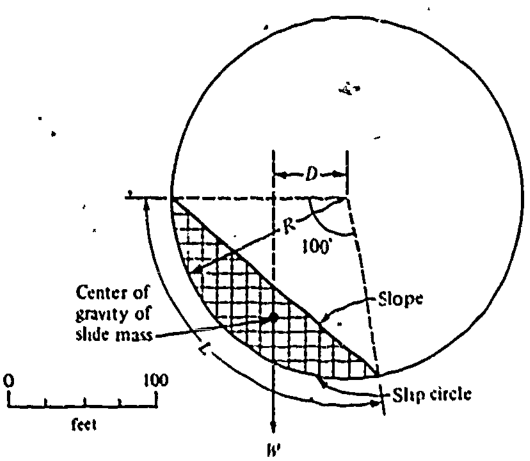


FIG. 26 Stability-analysis cross section of a homogeneous soil slope. $S = 800$ lb/ft^2 (given). $\theta = 100°$ (scaled from cross section). $R = 120$ ft (scaled from cross section). $D = 50$ ft (scaled from cross section). $W =$ (area [5100 ft^2] × thickness [1 ft] × density [120 lb/ft^3]) = 612,000 lb.

Figure 26 illustrates an example of moment analysis of a soil. As in Figure 24, English system units are used to facilitate comparison with examples in the literature. The area of the slide mass, determined by counting squares (51 × 100 square feet per square), is 5100 square feet, and the weight of 1 cubic foot of soil is given as 120 pounds.

The equation for the length of L = (angle subtended by the arc/180°) × π × radius R; in this example, $L = (100°/180°) \times 3.15 \times 120 \text{ ft} = 210 \text{ ft}$.

Therefore, with all parameters known and assuming a 1-foot-thick slice is being analyzed, the safety factor

$$\text{S.F.} = \frac{SLRT}{WD}$$

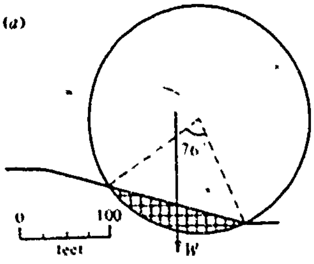
$$= \frac{800 \text{ lb/ft}^2 \times 210 \text{ ft} \times 120 \text{ ft} \times 1 \text{ ft}}{612{,}000 \text{ lb} \times 50 \text{ ft}} = \frac{20{,}160{,}000}{30{,}600{,}000} = 0.67$$

Because the safety factor is less than 1, the slope is unstable and should fail.

Problem 4

Drawn below are cross sections of three different soil slopes. Determine the safety factor and the stability for each, given that the thickness of the slice is 1 foot, the unit soil weight is 120 pounds per cubic foot, and the soil shear strength S is 800 pounds per square foot.

(*a*)

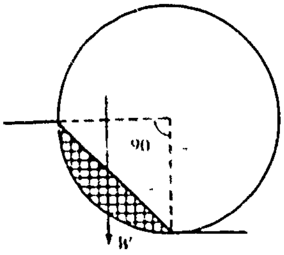


L =

$$\text{S.F.} = \frac{(S)(L)(R)(T)}{(W)(D)} =$$

Stability

(*b*)

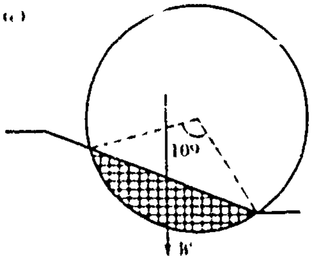


L =

$$\text{S.F.} = \frac{(S)(L)(R)(T)}{(W)(D)} =$$

Stability

(*c*)



L =

$$\text{S.F.} = \frac{(S)(L)(R)(T)}{(W)(D)} =$$

Stability

What is the gradient of each of the slopes in degrees and in percent slope?

$$\left(\text{Percent slope} = \frac{\text{vertical distance}}{\text{horizontal distance}} \times 100\right)$$

Slope	Degrees	Percent slope
a		
b		
c		

LANDSLIDE CONTROL AND CORRECTION

Landslides are nature's method of achieving slope stability or, more elaborately, that condition of quasi-equilibrium in which a slope is steep enough to permit its products of weathering and erosion to be transported away and yet not so steep that it will fail suddenly by mass movement. When in the proximity of homesites or other man-made structures, however, a landslide may be a very expensive and disastrous means of attaining stability—one in which the solution is far worse than the problem (Fig. 27). However, corrective measures can be taken to prevent incipient landslides—most often by controlling the *drainage*, *grading* the slopes, constructing *retaining walls*, or by combinations of the three.

Controlling the drainage is generally the least expensive way to stabilize a slope and often the most effective. The goal, for reasons given earlier, is to minimize the amount of moisture seeping into the slope. One method is to coat the slope with a sealant or cover it with plastic, as is done in some regions when slides occur during heavy rainfall and extensive damage is imminent. However, most drainage controls involve directing the water away from the slope. This may be done by paving areas near the tops of slopes and collecting the runoff in gutters, or by digging cutoff trenches filled with crushed rock or gravel to intercept and divert the flow of ground water from the area of concern.

Drilling horizontal wells containing perforated pipes is a common way of dewatering large slopes, especially along highway cuts. These pipes are designed to intercept the flow of water through the slope and carry it off rapidly to some central sump or drain; they are sometimes visible as many interconnected pipes at the base of a slope along a highway. Planting vegetation that draws much moisture from the ground is another excellent and beautiful means of keeping slopes dry. Extensive ground cover, especially of broad-leaved plants, also helps to prevent light rainfall from ever reaching the ground.

A more elaborate but very effective method of preventing slope failures involves changing the shape of the slope by grading. Grading techniques are intended to reduce the slope gradient, and this is achieved most effectively by removing material near the top of the potential slide mass and placing it near the base as a recompacted buttress fill. In addition to reducing the gradient, this procedure removes material from the area where additional weight tends to initiate slides, and the buttress fill prevents further movement by adding weight to the toe of the slide area. Sometimes there is insufficient space available to reduce the gradient significantly; in plan view, a cliff 25 meters high covers much less horizontal distance if nearly vertical than if gently sloping. In these instances, a common alternative is to bench or cut steps into the slope. Small gutters at the base of each step direct slope runoff away from the slide areas. Interrupting the slope gradient with benches also tends to reduce the velocity of runoff over the slope and thereby decrease slope erosion.

If the preceding methods of slope control prove ineffective, some sort of retaining structure must be built. In its simplest form, it is a sturdy, deeply embedded wall at the base of a slope, generally backfilled with drain rock and provided with outlets through the wall so that excessive hydrostatic pressures cannot

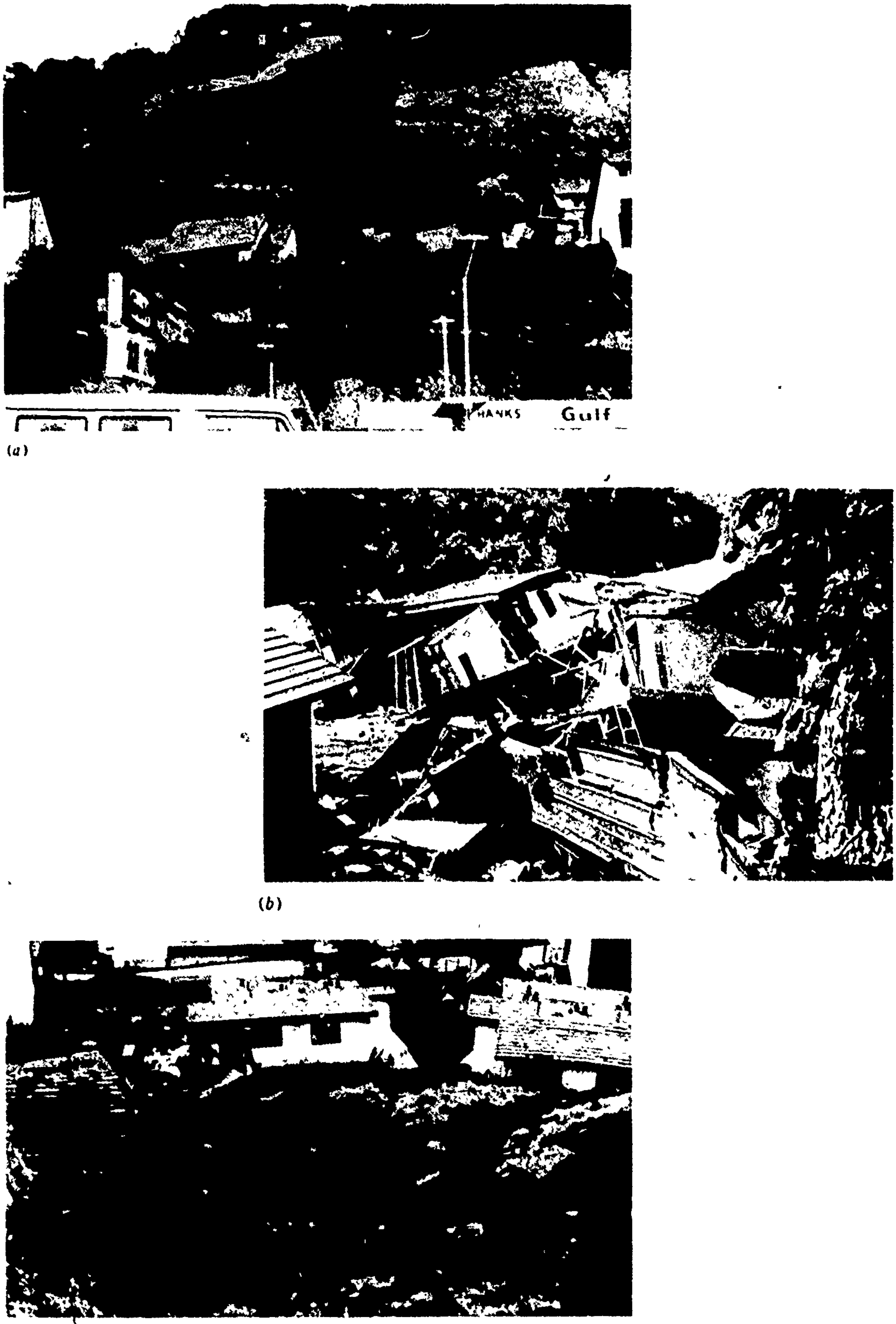


FIG. 27 Damage caused by the Red Rock Hill landslide in San Anselmo, California, the slide occurred suddenly in the winter of 1967-1968 after a period of very heavy rainfall. (*a*) Landslide scar, (*b*) apartment complex destroyed shortly after construction was completed but, fortunately, before the tenants to be moved in, (*c*) apartment complex pushed ahead of the rapidly moving landslide.

build up at the base of the slope. More elaborate approaches include rock-filled cribbing, deep piles to consolidate the slope, heavy wire mesh to prevent rock falls, and rock bolting together layers of rock when their structural attitude is potentially hazardous.

Special situations often require unique solutions (Fig. 28). During the construction of Grand Coulee Dam on the Columbia River, a refrigerant was pumped through pipes forced into a slowly moving slide mass which was endangering the project. The slide material was a saturated silt, and the refrigerant froze the pore water in effect cementing the silt and, thereby, increasing its strength and halting the slide. Other slide masses, depending on the materials of which they are composed, can be hardened by cementation, chemical treatment, or *electro-osmosis* - a method in which an electric field is applied to a clay mass and the interstitial water is forced to flow from positive to negative electrodes implanted in the ground.

FIG. 28 Water pipeline, normally underground, rests on ground surface where, encased in protective steel sleeve, it crosses an active mudflow.

MISCELLANEOUS RELATED EXPERIMENTS

The following experiments demonstrate man-made slope instabilities, quicksand, piping, and rapid reservoir drawdown. Those utilizing water should be performed with the landslide box installed in a plastic pan to prevent water damage to unprotected surfaces. After one completes each experiment, the apparatus should be cleaned and dried and the sediments dried, and if necessary sieved, before returning them to their respective storage containers.

Equipment

Landslide box
Fine sand
Wooden coffee stirrers or ice-cream sticks
Medium or coarse sand, or fine gravel
Plastic pan (optional)
Lead weight
One-foot grooved plastic ruler
Steel ball
Ten-centimeter nail
Clay
Sieves (optional)

MAN-MADE SLOPE INSTABILITIES

The alteration of existing slope conditions during the construction of houses on, or adjacent to, steep slopes often leads to unstable conditions. The following experiments simulate some of these situations

Procedure

a Using procedural steps *a* and *b* of Laboratory Experiment 4, prepare in the landslide box a slope of fine sand at its natural angle of repose. Then carefully remove material from the toe of the slope; this is analogous to increasing the backyard area of a house at the base of the slope.

Describe what occurs when material is removed from the toe.

How might material be removed and the slope stability be preserved?

b Repeat step *a*, but before removing the material construct varied kinds of retaining walls with the wooden coffee stirrers or ice-cream sticks.

Draw a cross-sectional view of the structure that most successfully resists slope failure.

c Repeat step *a* with material of different grain size (e.g., coarse sand).

Compare the results with those observed using fine sand.

d With the landslide box in the plastic pan, construct in the box a slope of fine sand at its natural angle of repose. Then, carefully add water to the top of the slope.

Describe the consequences. (Varied results will occur depending on how the water is added)

What situation in nature might this experiment simulate?

e With the cleaned and dried landslide box in the plastic pan and with a slope of dry fine sand at its natural angle of repose in the box, cut a small bench midway up the slope to simulate the excavation of a foundation pad for a house. Place the lead weight (representing a house) on this bench.

Note the consequences when:

1 Water is added to the top of the slope.

2 The toe of the slope is excavated.

3 The steel ball is rolled repeatedly down the ruler to strike the back wall of the box, simulating an earthquake.

QUICKSAND

The ability of noncohesive earth materials, primarily sands, to bear weight is significantly decreased by fluids bubbling up through them under pressure. Only noncohesive materials are affected because the property of cohesion present in clays prevents the ready passage of fluids through the clays.

Erroneous impressions have been publicized concerning the ability of sands under fluid pressure to bear the weight of a man. If nonturbulent pure water is able to buoy up the weight of a man, certainly any material denser than water can buoy this same weight more readily. Any attempt to propel oneself through this denser medium would obviously be very difficult and would probably serve to displace material and aid settling within the quicksand. However, the belief that people or animals are somehow dragged down into quicksand is false.

Procedure

a With the white rubber hose connected at one end to the plastic syringe and at the other to the rubber stopper bearing the metal tube, clamp the water-filled syringe to the back wall of the landslide box and insert the stopper covered by the gauze filter into the middle hole in the bottom of the box. Then, after positioning the movable wall approximately 10 centimeters from the back wall and locking it in place with the wall pin in the appropriate hole in its handle, fill with fine sand the space between these walls to a level 4 centimeters from the top of the box, orienting the nail horizontally in the sand immediately over the central water inlet. Now, slowly expel the water from the syringe, and bubble it up through the stopper.

What happens to the nail?

b Increase the pressure of the water from the syringe.

Note the change in the subsidence of the nail.

c Change the orientation of the nail, and resume bubbling the water into the box.

Describe what happens to the nail.

d An interesting adaptation of this experiment employs dry clay as the sediment and compressed air as the fluid. Clean and dry the box, syringe, hose, stopper, and filter. Then, repeat steps *a* to *c* using dry clay in place of the sand and air in place of the water in the syringe.

Describe the results.

Why would this experiment not work as well with sand and air?

Why would this experiment not work at all with clay and water?

PIPING

When water moves with appreciable velocity through sand, it can pick up and transport grains, leaving voids in their place. This process may develop large holes where the sand ladened flowing water intersects a slope. In addition, surface subsidence often occurs above the zones of moving water.

Procedure

Replace the hose-bearing stopper in the bottom of the landslide box with the solid stopper, then, as in the quicksand experiment, position the movable wall roughly 10 centimeters from the back wall, locking it in place with the wall pin. After placing the box in the plastic pan, fill the space between the movable and back walls with fine sand to a level 4 centimeters from the top of the box, and saturate the sand completely so that the water stands above the surface of the sediment. Remove the lower cork in the movable wall, this cork is analogous to a wall drain plug.

Note the results, particularly what happens at the surface of the sand.

RAPID RESERVOIR DRAWDOWN

When severe flooding is expected, the level of water in flood-control reservoirs is often lowered rapidly to make room for the anticipated influx. When this occurs, the ground water in the reservoir banks will for a short time be at a higher level than that of the main water body.

With removal of the balancing pressure of the reservoir water against the banks, the weight of ground water within the soil tends to aid the development of a sliding failure. If the soils are noncohesive and permeable, piping may also be initiated.

Procedure

a With the movable wall and its handle removed from the landslide box, construct against the back wall of the box a slope from a mixture of fine sand and clay that is at least 6 centimeters high and has a steep gradient. Slowly flood the box with water to the level of the top of the sediment mixture.

Explain any adjustment in the slope gradient.

b From the bottom of the box, remove the rubber stopper nearest the front wall, and allow the water to drain off.

Describe the resulting conditions.

EXAMPLES OF TYPES OF MASS MOVEMENT

CREEP

Slow downhill movement by *creep* is the result of gravitational forces acting on near surface materials. It is the dominant process of mass wasting and yet the least dramatic in terms of surface manifestations. Measured rates of movement of surface soils and rock fragments may be as low as a few millimeters per year on gentle slopes of less than 5° or as high as 10 centimeters per year on slopes of 40°.

The effect of creep is greatest at the surface and gradually decreases with depth because there is no sharply defined failure plane between particles that have moved and those that have not. The force of gravity is aided by alternate periods of expansion and contraction of the soil expansion and contraction associated, respectively, with wetting and drying (in soils with a high clay content) or with freezing and thawing (in more granular soils). When expansion occurs, soil particles are lifted upward at right angles to the slope. On contraction, the pull of gravity draws the particles downward vertically, regardless of the angle of inclination of the slope. The result is a net downslope movement. This mechanism also accounts for the slow seasonal movement of large rock fragments down a slope, when caused by expansion and contraction due to the freezing and thawing of trapped waters it is called *frost heaving*. Because of its dependence on periodic alternations, creep is primarily a seasonal but not a continuous occurrence; and because the effect of movement decreases with depth, there are no well-defined landslide scars.

Additional factors affecting slope movements by creep are reworking of surface soils by burrowing animals such as earthworms and rodents, growth of vegetation, causing soil wedging, decay of vegetation, causing voids that become filled by particles from higher in the slope, and solution of soluble minerals in the soil, likewise creating voids that may fill with materials from upslope. The continual trampling by grazing animals on some slopes forms small steplike features called *terracettes* which appear to move slowly downslope as grazing continues, however, some terracettes have other origins and may be related to swelling phenomena in clays.

Surface evidence for creep is very common but less obvious than evidence for other types of mass movement. The downslope tilting of man-made structures, such as telephone poles, fences, retaining walls, and monuments, is very distinctive. Trees with trunks bowed concavely upslope are also clear indicators of slow downslope movements, when creep occurs, the trunks of young trees are tilted downslope in the direction of the movement, but as growth proceeds, the trees continue to grow vertically, causing their trunks to develop their diagnostic bend (Fig. 29).

SOLIFLUCTION

Solifluction is an imperceptible type of downslope flowage of water-saturated surface materials that occurs normally in periodically frozen areas. In regions where the ground freezes to great depths, thawing occurs

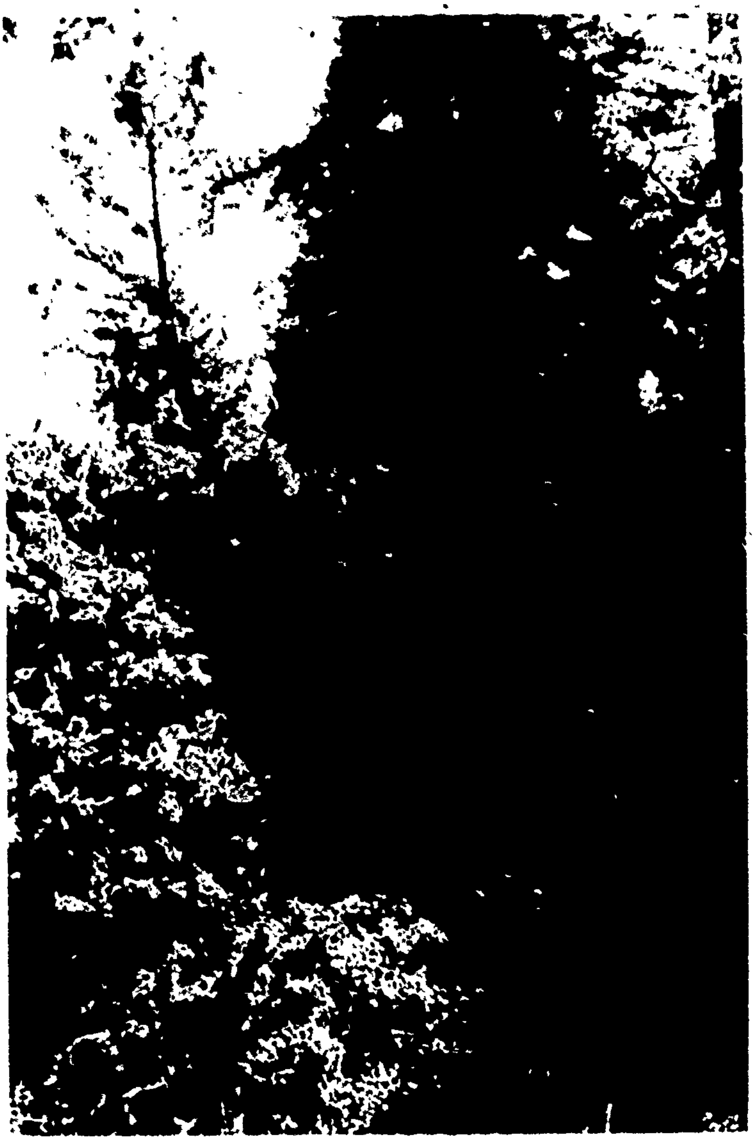


FIG. 29 Curved tree trunk bowed upslope, indicating surface movement to the left.

slowly from the surface downward. When thawing begins, surplus water cannot percolate into the still-frozen ground, and the surface soils become saturated. With their weight increased, these soils then flow very slowly downslope, often forming lobate features called *solifluction lobes.*

Solifluction proceeds at rates slightly greater than those for creep, but the main difference between the two is in the moisture content of their materials. Solifluction requires a very high moisture content, whereas creep may occur in materials that are completely dry. In arctic regions, solifluction is an important mechanism for transporting large amounts of debris from higher to lower elevations.

ROCK GLACIERS

Another remarkable type of slow flowage involves poorly sorted angular rock fragments and occurs in the valleys of mountainous frozen regions. These rock materials form tonguelike ridges or lobes which apparently flowed down out of the mountains. They generally contain great thicknesses of rocks from the higher cliffs, and their lobate form suggests that they have moved down the valley by some sort of flow mechanism. They are called *rock glaciers* because of their similarity to glacial forms, and they are believed to move as a result of the flow of the interstitial ice surrounding the rock fragments Their formation requires steep cliffs, a near-glacial climate, and bedrock that is broken by frost action into coarse blocky debris with large interconnected voids Some move as much as 50 centimeters per year.

COMPRESSED-AIR-LUBRICATION

In some recently investigated landslides, the form of the slide mass and nature of the materials suggest a mode of movement significantly different from anything previously studied. The Blackhawk slide in the San Bernardino Mountains of southern California is one example. A thin sheet of intensely fractured marble occurs on an alluvial fan surface that slopes gently away from the mouth of Blackhawk Canyon at an angle of about 2½°, the sheet is in the form of a lobe about 3.2 kilometers wide and 8 kilometers long

The slide mass comprises an almost pure marble breccia that conspicuously lacks any fine grained silt or clay material. Strangely, surface wrinkles on the slide mass are concave downslope instead of convex (the normal attitude found in other similar slides), and elevated sand ridges are present along its edges These unique surface forms, coupled with the puzzle over how such a mass of material could have traveled so far on such a gentle slope, have led investigators to hypothesize that the slide mass traveled on a layer of *compressed air* that was trapped during the initial mass movement much like a giant hovercraft moving rapidly just a few inches over the ground surface.

As the slide mass is present at the base of a mountain range about 500 meters high, the velocity of a rock fall from such a height could have been enough to quickly trap and compress a layer of air beneath the falling mass. This layer of compressed air would then act as a lubricant, allowing the material to travel such a great distance. The anomalous surface features associated with the slide might also owe their form to this unique mode of movement. This hypothetical mechanism, although still only poorly understood, is being used to explain a host of puzzling landslide features. Prime among these are the large volumes of material that have moved great distances at enormous velocities while traveling over surfaces of very low gradients

FALLS

Through mass wasting, rocks often accumulate at the base of a cliff in a cone-shaped surface deposit known as a *talus*. Taluses are common in areas where the rocks are heavily fractured or jointed, or where resistant rock units are underlain by comparatively nonresistant materials. Both of these situations favor accumulation of large angular blocks at the bases of slopes, the gradients of which are related to the composition of the rocks and to the distance and kind of surface over which they have fallen,

The farther rock falls down the slope, the more it is broken up, and the finer it becomes Where particles of varied sizes are introduced at the top of the talus, however, the larger rocks owing to their greater momentum -generally travel farther down the slope and accumulate near the base. This results in a progressive downward sorting of rock fragments from finer to coarser.

The amount of vegetation growing on a talus cone indicates the activity on that slope. Continually falling debris prevents vegetative growth, whereas a healthy stand of trees and shrubs indicates that little material is being introduced at the head of the cone and that weathering of the rocks to soil is proceeding without much distrubance (Fig. 20).

A longitudinal profile of a fresh and active talus is generally quite straight, with a constant slope angle of about 35°. This gradient approximates the angle of repose for the constituent rock fragments. Variations occur when fine materials are introduced and become lodged between the coarser blocks to form locally steeper segments. Increased weathering on an inactive part of a talus also reduces the size of the rock fragments and locally decreases the gradient. Similar profiles, representing other dynamic-equilibrium conditions, may occur in stream drainage systems, on hill slopes, and along the coast. This similarity indicates that uniformly consistent land-forming mechanisms operate over the entire surface of the earth a reasonable expectation considering that the materials involved (rocks, soil, and sediment) are essentially the same and only the medium through which they move (air, water, and ice) varies. Understanding a few basic principles of land-forming processes, therefore, enables one to appreciate why the landscape appears as it does.

Although relatively unspectacular talus accumulations represent the most common type of rock fall, much larger catastrophic rock falls, such as the one at Vaiont Dam, have occurred throughout history. They become more common (1) where humans interfere with natural slope conditions and (2) where the geologic structures or lithologies favor such movement.

A classic example of the first situation occurred in 1881 in Elm, Switzerland, where, as a result of extensive slate quarrying, a block 600 meters high had been undercut and the slate beneath it removed. A large fissure developed behind the undercut block, and the block became increasingly saturated with runoff from late summer rains, thereby weathering and weakening the already shattered rocks within. A short time later the entire block about 7.6 million cubic meters of material crashed suddenly to the quarry floor, filled the valley at its base, rushed up the opposite slope to a height of about 100 meters, and destroyed everything in its path leaving 115 persons dead in its wake. The great velocities of the falling debris in this rockfall and the distances it traveled, according to eyewitness accounts, suggest that the moving mass may have been buoyed up on a cushion of compressed air.

When triggered by the Good Friday earthquake on March 27, 1964, some 30 million cubic meters of rock fell 600 meters down the side of Chugach Mountain near Cordova, Alaska, and then slid at high speed 5 kilometers across the nearly level Sherman Glacier. The movement of this large, steeply dipping highly jointed tabular block of massive sandstone and argillite (which composed the western uppermost face of a Matterhorn-like peak–now informally called "Shattered Peak") occurred along a bedding surface within the sandstone–an example illustrative of geologic controls.

The Alaska landslide is also noteworthy because it appears to have slid across a part of Sherman Glacier without having scoured much snow off the surface. This suggests that the movement occurred on a cushion of trapped compressed air, similar to those hypothesized for the Blackhawk and Elm slides. Because part of the lower end of the glacier has been covered by an insulating layer of slide debris, geologists are also studying the expected advance of the terminus to determine the effects of this sudden change in the thermal regimen.

SLIDES

The great variety of mass movements caused by sliding of two or more units past one another reflects the complexity of this type of displacement and may be best described through a number of typical examples. When the failure surface is planar, the slide is termed a *block glide*. When large blocks remain intact and slide on curved failure planes, the slides are termed *slumps* an extremely common type of slope failure.

An example of a block glide occurred at Point Fermin, near Los Angeles. In addition to the major block glide itself, which took place along the bedding surface inclined 15° seaward, small rotational masses slumped into the gap at the rear of the main block, and imminent rockfalls are present at the sea cliff. This block has been moving sporadically and slowly since 1929, most of the slippage occurring after periods of heavy rainfall.

One of the most distinctive features of a slump is that the entire block usually rotates backward during its descent as a result of sliding on a curved failure surface. In the southern Colorado plateau, such blocks have developed in cliffed sections of gently dipping strata composed of alternating sandstones and shales. Wetting of the shales causes them to act as a lubricated slip surface upon which the sandstones then slide. This distinctive type of slump has been called a *Toreva block*, after a nearby Indian site, and as the present climate is semiarid, these prehistoric slides are thought to have occurred during the Pleistocene Epoch, when the region is believed to have been humid.

On the evening of August 17, 1959, a severe earthquake jarred the area along the Madison River west of Yellowstone National Park, setting off one very large landslide and several smaller ones. At a nearby campground, the mother of a family saw her husband "grasp a tree for support, then saw him lifted off his feet by the air blast and 'strung out like a flag' before he let go. Before she lost consciousness she saw one of her children blown past her and a car tumbling over and over." (Hadley, 1964.) The tremendous blast of air was caused by a large landslide on the side of the valley opposite the campground. Approximately 31 million cubic meters of rock and debris slid into Madison Canyon, damming Madison River (to form Hebgen Lake), burying the nearby highway to depths of 60 meters, and claiming 26 lives.

This particular type of mass movement is called a *rockslide*, a distinctive type of slide failure in which the rocks are broken up and moved as a large disaggregated mass, in contrast to the slumps and block glides previously described. The geologic conditions were such that a slide in this area was inevitable, awaiting only the appropriate initiating conditions. In this case, it was the earthquake that jarred loose a large block of sheared and altered schist and gneiss that rested about 200 meters above a deeply incised, undercut part of the Madison Canyon.

A famous rockslide occurred in 1903 in the coal-mining town of Frank, Alberta, when some 31 million cubic meters of rock crashed downward from the crest of Turtle Mountain, 1000 meters above the town. Seventy persons lost their lives in this disaster a disaster that could have been predicted had the geologic conditions been known.

Joints in the limestone forming Turtle Mountain dipped steeply toward the valley and were being enlarged and extended by solution and frost wedging. The valley itself is underlain by weaker shales that were slowly being deformed by the weight of the limestone above Coal mining in the valley was further weakening the base upon which the limestone rested, and earthquake tremors had earlier shaken the entire region. Finally, the limestone mass broke loose and, at speeds estimated at 100 kilometers per hour, rushed down the mountain side.

Although initially a rockslide, this heterogeneous mass of rock, soil, and debris is thought to have moved mainly as a viscous fluid in which the material, although dry, flowed in a manner analogous to that of a liquid. This type of mass movement has been termed a *rock avalanche* and is a very complex form of slope failure not thoroughly understood but very common. It is especially common in mountainous terrain covered by blankets of snow which are readily capable of incorporating rock and soil into a flowing mass.

FLOWS

The highly varied physical conditions under which earth materials may exist account for the many kinds of slope failure in which flowage is the primary mode of movement. As indicated in Table 1, different types of flows are possible depending upon the size, variety, and moisture content of the materials.

The most destructive landslides in recorded history, and a dramatic example of dry flows, were the *loess flows* that occurred in 1920 in Kansu Province, China. The great Kansu earthquake of December 16 jarred loose gigantic masses of loess (unstratified deposits of windblown silt) and moved them down mountain sides, inundating populated valley areas up to 5 kilometers in length. More than 100,000 people were killed in this catastrophe, but because of poor communications word did not reach the rest of the world until months after the disaster. (As the Chinese have no term for landslide, they aptly described the devastated area as *Shan tso-liao*—where the mountains walked.)

Among the more dramatic events of this disaster was the burial of Ma the Benevolent, a famous Moslem fanatic, and 300 of his followers as they were meeting in conclave to proclaim a holy war. While the plotters knelt on their prayer mats, an avalanche sealed the cave in which they had gathered, and only the watchman at the entrance survived. The others were so deeply buried that not even after months of digging in an area over 1.5 kilometers square were the Moslem searchers able to recover the bodies of their leaders.

In another district, a mountain topped by a temple slid into a valley. A little beyond, a road bordered by poplar trees rode the crest of a slide for 1.2 kilometers without apparent damage to the trees or even to the birds' nests in their branches. Elsewhere, an astonished peasant peered from his window in the morning and discovered that a high hill had invaded his homestead, its foot having come to rest only a meter or so from his hut.

In another village, the only survivors were a couple, each of whom was over 70 years old. They were spared only because their children, with unusual disregard for filial piety, had banished them to a house on the outskirts of the town. Inhabitants of the area interpreted the death of their descendants as proof that Heaven had punished the family for its lack of parental respect.

Although the loess flows occurred in a dry state, most *mudflows* require saturated or near saturated conditions. As the name implies, mainly fine-grained materials are involved, but mudflows are capable of moving large boulders and, depending on the moisture content and the slope, move as fast as 35 centimeters per second. Mudflows approximate most closely viscous liquids in form and mechanism of movement, and they occur most often after periods of heavy rainfall (Fig. 30).

The Los Angeles area, for example, is beset with many natural hazards, prime among which are the disastrous mudflows that occur after some heavy winter rains. The dry summers produce a severe fire hazard as well, and when a particularly bad fire season is followed by a wet winter, the danger is

FIG. 30 Mudflow in saturated clays. The lobate forms approximate those of a viscous liquid.

significantly increased. The fires destroy the natural ground cover, allowing extensive erosion of the surface to occur. When this happens on steep slopes, massive mudflows which often follow sometimes move so fast and with such force that people are unable to escape from their path, notable examples occurred during the disastrous winter of 1968-1969.

On October 21, 1966, after a period of very heavy rainfall, 144 persons (including 116 young children who had just arrived at school) died when tons of water-logged coal-mine spoil rushed down the side of Mynydd Merthyr at Aberfan, Wales. The coal-mine waste piles, known as *spoil tips*, are generally located in the most convenient location near the mine, with only minor regard to the matter of slope stability. In this catastrophic instance, the spoil tips rested on the slope of a hill above the town. After a period of heavy rainfall, during which the weight of the material was increased and its stre reduced, the entire mass suddenly flowed down the hillside.

Up to that time, little thought had been given to the stability and safety of spoil tips. Following a lengthy court of inquiry, extensive investigations were made into the safety of existing tips, and emphasis was placed on the need for a fuller awareness of the principles that underlie even the most commonplace of human interferences with nature.

In the summer of 1925, a landslide blocked the Gros Ventre River 6.4 kilometers above Kelly, Wyoming. In this slide, soil and rock became disaggregated immediately after the initial movement and flowed down the side of Sheep Mountain as a *debris flow*. About 38 million cubic meters of rock, soil, and vegetative debris plunged down the valley side and rushed some 120 meters up the opposite wall before settling back into the valley and damming the river.

The mass that slid was part of a jointed sandstone unit which rested on a clay bed above a limestone formation. The structural attitude was such that all beds dipped gently (15 to 20°) into the valley. It was only a question of time until the clay layer became sufficiently lubricated by rainfall that it could no longer bear the weight of the overlying sandstone. This occurred on the afternoon of June 23, following heavy rainfall and snowmelt of the preceding spring.

As is apparent from the preceding examples, mudflows occur in highly varied forms. In regions of explosive volcanic activity, the fine pyroclastic material that mantles the slopes is especially susceptible to flowage. If the loosely consolidated, fine powdery-ash debris becomes water saturated, it readily flows with the consistency of a thick paste. Such a *volcanic mudflow* overwhelmed and buried the Roman city of Herculaneum when Mount Vesuvius erupted in A.D. 79.

The Alaskan Good Friday earthquake of 1964 caused a great variety of landslide damage. The most destructive of these slides was at Turnagain Heights in Anchorage, where the calamitous failures resulted from a loss of strength in sand lenses underlying massive clay deposits. Apparently, the earthquake's ground motions liquified the interbedded sands and silts, forcing them to flow out from beneath the clays, which then had to readjust, causing large slumps. In some places, they dropped 12 meters and moved laterally as much as 700 meters. Whenever great thicknesses of sand were present, the shaking from the earthquakes resulted in particle readjustments within these noncohesive materials. Subsidence took place where the sediments were restricted and could not flow, and structures, such as telephone poles, were suddenly raised 1 to 2 meters as the ground settled beneath them.

At Valdez, and Seward, Alaska–both coastal communities built on saturated unconsolidated deltaic deposits–the greatest damage occurred at the docks, where large *submarine slumps* and *mudflows* destroyed most of the structures. Similar submarine flows also accompanied the Grand Banks earthquake of November 18, 1929, in this area southeast of Newfoundland the movement of a density current initiated by the slumping was measured precisely as it ripped across and severed 13 transatlantic telegraph cables.

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APPENDIX A: MODULE EQUIPMENT AND MATERIALS

Required (supplied with the equipment package)

Inclined-plane apparatus (Fig. 3), with base, two boards, thumbtacks, and two sheets each of "clay" paper (600 grit), fine sandpaper (120 grit), and coarse sandpaper (36 grit)
Sandstone block, roughly 5 X 5 X 2 cm.
Protractor
Lead weight.
Plastic squeeze bottle
Two beverage cans (one with perforations in the base), both open at the top
One-cup plastic measuring cup
Landslide box (frontispiece and Fig. 6), with clamp-on plastic syringe; white rubber hose; four rubber stoppers, two smaller and solid, and two larger one solid and one with metal tube inserted, gauze filter, and knurled brass wall pin
One-ft (30.5-cm) grooved plastic ruler
Piston corer (Fig. 6)
Shear-strength testing apparatus, (Fig. 7), with rectangular wooden base plate, white plastic ruler, 1/2-gallon plastic jar with screw top and attached trapezoidal Plexiglas plate; two 5/16-inch wood dowels and cotter pins; and loose trapezoidal Plexiglas sheet (= upper plate of load applicator).
One-thousand-ml graduated cylinder
Red rubber hose and clamp
C clamp
Ten-cm nail
One-in. steel ball
Wooden coffee stirrers or ice-cream sticks

Required (not supplied)

Quart container each of:
a Clay*
b Fine sand or silt
c Medium or coarse sand*
d Mixture of sand, silt, and clay (approximately 50 percent medium-coarse sand, 25 percent silt or fine sand, and 25 percent clay)
e Fine gravel, angular or rounded, with diameter of roughly 0.5 cm

For sieve sizes, see Appendix B.

Because of their weight and the cost of shipping, the above materials are not supplied with the equipment package, but they can be purchased inexpensively (generally in 100-lb sacks) at most building materials suppliers. Fire clay and Monterrey sand work well for the clay and medium-sand materials, and they can be combined to form the mixed sediments; roofing gravel is suitable for the fine gravel. If all the materials are not available locally, those marked above with an asterisk should be given preference as they are the most important and demonstrate best the principles discussed in the text.

Accessories (not supplied)

Sieves. A set of graduated sieves is useful for separating sedimentary materials mixed for, or during, the experiments. If none is available for laboratory use, an adequate set of four plastic sieves (with wire-screen mesh numbers 6, 20, 40, and 100)–designed for use with ESCP materials–may be purchased for $9.50 (at the time of publication) from Hubbard Scientific Company, Northbrook, Illinois 60062, or from six interlocking plastic sieves (with brass wire-screen mesh numbers 10, 18, 35, 60, 120, and 230) is marketed by both Hubbard and Ward's (again, at the time of publication) for $28.00, the product is called a sieve screen set by Hubbard, a screen-plankton sieve set by Ward's.

Plastic pan, roughly 42 X 20 X 5 cm, in which inclined-plane apparatus and landslide box may be placed when used with water.

Multiple Utility of Equipment

The two most specialized pieces of equipment, the landslide box and the shear-strength tester, have additional experimental uses with geologic significance.

The *landslide box* may be used for (1) sedimentation experiments (e.g., building deltas and alluvial fans, demonstrating stratification), (2) geomorphic experiments (as a small stream table), and (3) structural experiments (e.g., deforming multicolored clay layers to simulate folds and faults).

The shear-strength tester may be used for structural experiments (e.g., determining force orientations–used in conjunction with strain ellipsoids; demonstrating properties of materials).

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APPENDIX B: GRAIN-SIZE SCALES FOR SEDIMENTS

Scientists and engineers who work with sediments commonly classify grains according to a size scale first proposed by Udden but modified later by Wentworth. Most of the grain-size boundaries occur at points such that one is twice the size of the next smaller grade. Because these boundaries are equally spaced on a logarithmic scale, Krumbein defined the phi unit (ϕ), whole-number multiples of which could serve to divide the entire size range of particles. Relationships among the scales are brought out in the chart that follows; note that the units shown indicate the *lower* boundary of a category.

U.S. Standard Sieve Mesh No.	Diameter*	Phi ϕ	Wentworth Size Class	
	>2.56. cm (about 1 in.)	-8	Boulder	
	64 mm	-6	Cobble	
<5	4 mm	-2	Pebble	Gravel
10	2 mm	-1	Granule	
18	1 mm	0	Very Coarse Sand	Sand
35	0.5 mm	1	Coarse Sand	
60	0.25 mm	2	Medium Sand	
120	125 μm	3	Fine Sand	
230	62.5 μm	4	Very Fine Sand	
320	31 μm	5	Coarse Silt	Mud
	15.6 μm	6	Medium Silt	
	7.8 μm	7	Fine Silt	
	3.9 μm	8	Very Fine Salt	
	< 3.9μm	> 8	Clay	

*1 cm = 10 mm = 10,000 micrometers (μm), formerly called microns (μ).

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