CHAPTER 10
MASS WASTING

1. INTRODUCTION

1.1 Everything at or near the surface of the Earth is pulled toward the Earth by the force of gravity. ("Gravity: it's a law you can live with.") That includes all Earth materials, rock and regolith. This is one of the central concepts of this course. Its importance lies in the fact that under certain circumstances those materials are moved downslope by the pull of gravity. *Processes of downslope movement of surficial Earth materials under the pull of gravity* are collectively termed ***mass wasting***. (I've always thought that term to be rather infelicitous, but there it is.) This is a good time to look at the two background sections on gravity at the end of this section.

1.2 You might view the problem of mass wasting in terms of an atrocious paraphrase of a famous quotation: "To move downslope, or not to move downslope?" The criteria for initiation of downslope movement of Earth materials by gravity are not straightforward, but they are of great practical as well as theoretical importance: mass-wasting events are responsible for enormous loss of life.

1.3 Processes of mass wasting are highly varied in three important respects:

- mass of material involved
- speed of movement
- nature of movement

Masses of material vary from tiny mineral grains tumbling downslope to enormous masses with volumes of rock and mineral material as great as thousands of cubic kilometers. (Yes, thousands; that's not a typo.) Speeds range from imperceptibly slow, less than a meter per year, to hundreds of meters per second. The nature of movement ranges from intact masses, which retain their original structure, to those that become thoroughly mixed and homogenized during the movement. Given this wide range of characteristics, it should not come as a surprise to you that classification is difficult and terminology can be confusing.

BACKGROUND: GRAVITY

1 Everybody knows about gravity. For the sake of clarity, though, here's some background material on it.

2 First of all, there's a distinction between gravitation and gravity. ***Gravitation*** is the more general concept: it's *an attraction between any two bodies of matter in the universe*. As with many important things in physics, it began with Newton: he formulated what is now called *Newton's law of universal gravitation*, that any two bodies of matter exert an attractive force upon each other that's proportional to the product of their masses and inversely proportional to the square of the distance between them. (It's one of a number of manifestations of what physicists call "inverse-square laws".) Does it surprise you to learn that gravitation is an extremely weak force? It gets big only when one or both of the bodies is very massive, like stars or planets.

3 The Earth exerts a force of gravitational attraction upon us, and upon everything else on Earth as well. That's what's called the ***force of gravity***. (We exert an equal and opposite force on the Earth, but we usually don't bother to think about that. It probably seems ridiculous to you to think that each of us exerts that big force on the whole Earth, but it's true.)

4 What we call ***weight*** is just *the force of gravity the Earth exerts on us or on other bodies of matter*. It's important to be clear on the distinction between mass and weight. The *mass* of a body is *a measure of the amount of matter of which that body is composed*; the *weight* of a body is the force of gravity the Earth (or any other solar-system body, for that matter) exerts on the body. That's why the astronauts weighed so much less when they were on the Moon, and why astronauts in deep space are weightless, even though they are not massless.

BACKGROUND: THE DOWNSLOPE COMPONENT OF GRAVITY

1 The force of gravity that the Earth exerts on us is directed toward the Earth's center of mass—which is almost identical to the Earth's center of volume. (It's just generally called "the center of the Earth".) The way "horizontal" is defined, anywhere on Earth, is just *the plane that's perpendicular to the direction of the force of gravity, at that locality*. Any still water surface is coincident with that horizontal plane—because if the surface were not horizontal, it would be sloping, and gravity would pull the water down the slope until no slope remains.

2 That leads us directly to the important idea that the force of gravity can be viewed as *having a part that acts in all directions that are not coincident with the horizontal plane*. That force is called the ***component*** of the force of gravity in that particular direction. To deal with that quantitatively, you need to know something about the mathematics of vectors. (A vector is a quantity that has both magnitude and direction, and behaves according to a particular set of rules; no details here.) You can resolve a vector into components along any set of axes, by certain mathematical rules. Figure 10-1 shows how the force of gravity of a body resting on a sloping surface can be resolved into two components, one parallel to the surface and one perpendicular to it. What I want you to see in this is that the downslope component of gravity gets smaller as the slope gets gentler: it varies from the full force of gravity, in the vertically downward direction, to zero, on a horizontal, surface.

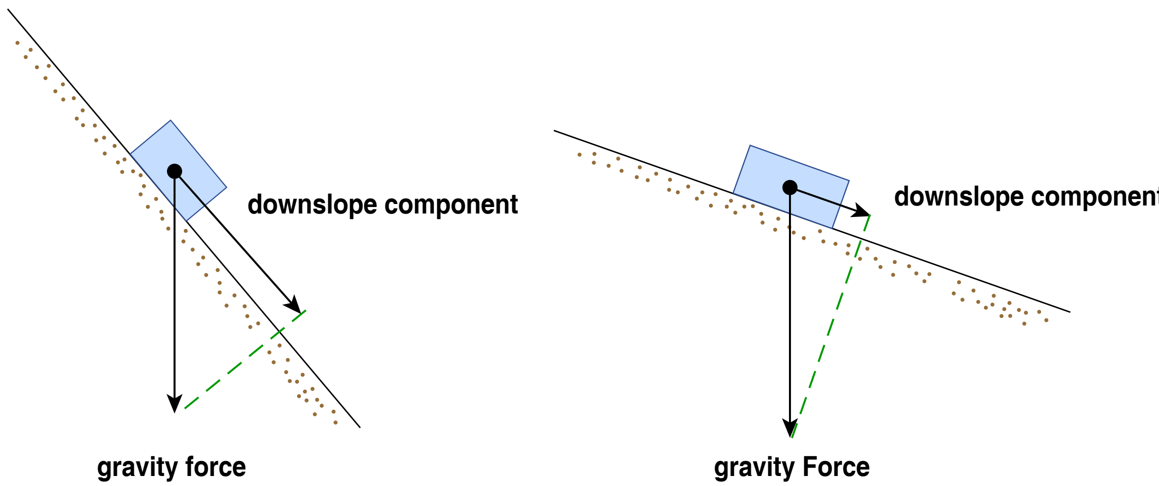

Figure 10-1. Resolving the force of gravity into a component in the downslope direction. The lengths of the arrows represent the magnitudes of the components of the gravity force. Left: a steep slope. Right: a gentle slope.

3 All of this should make good qualitative sense to you, because it's part of the human experience: we are pulled down a steep slope more than down a gentle slope. The same is true of all rock and regolith on the Earth's surface as well, and that's what's important for this chapter.

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2. THE CONTROLS ON DOWNSLOPE MOVEMENT

2.1 Envisioning the Problem

2.1.1 At this point we need to take a closer look at what controls whether a mass of material will slide down a slope. Just to get your thinking started, here are two seemingly dissimilar but actually closely related situations:

- Making a pile of dry sand by pouring the sand slowly and continuously down toward the same point (Figure 10-2A)
- Placing a thick layer of soil on a horizontal sheet of plywood and then slowly tilting the sheet until some or all of the soil slides off (Figure 10-2B)

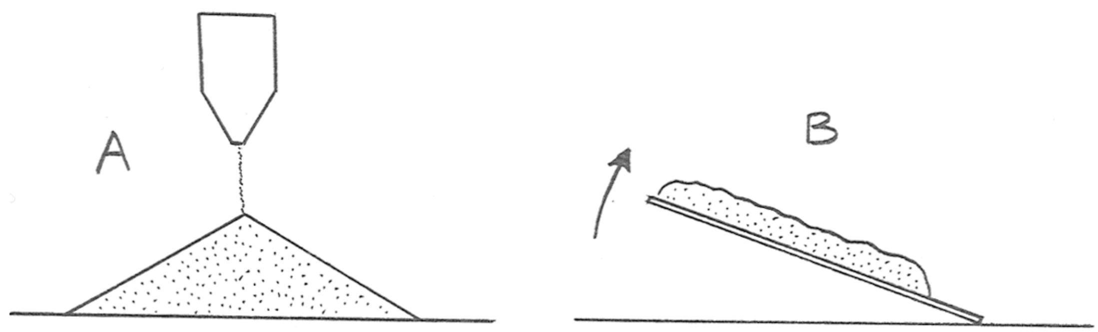

Figure 10-2. A) Making a pile of dry sand. B) Sliding a layer of soil off a silted plywood sheet.

2.1.2 You must know, from your own experience, that when you try to build the sand pile in Figure 10-2A to have steeper slopes, a surface layer of sand suddenly slides down the slope, thereby decreasing the slope angle. As you build the pile to a larger and larger volume, the alternation of slope-increasing intervals and slope-decreasing intervals balances out, resulting in a constant average slope angle. That angle is called the ***angle of repose***. For dry granular materials that are not extremely angular or jagged, the angle of repose lies in the range 30–35°. Very angular blocks, of the kind that are common on talus slopes in mountainous areas, have greater angles of repose, but seldom more than 45°. (To me, such slopes always seem greater than they really are when I'm walking on them.)

2.3 As you gradually increase the slope of the plywood sheet in Figure 10-2B, at some point the whole mass slide off the sheet. ("Duh", you're probably thinking.) As a variant on the experiment, however, you might make the upper surface of the sheet ribbed or corrugated, with the ribs running in the transverse (horizontal) direction. How would that affect the value of the slope angle at which failure takes place?

2.2 Analyzing the Problem

2.2.1 In both of the situations described above, we need to think in terms of the force of gravity on a layer of material in the shape of a slab with its upper surface at the ground surface and its lower surface some depth below the surface (Figure 10-3). If the slab is stationary (not moving downslope), then there must be a friction force that's exerted by the material underneath the slab on the material of the slab. We can place this imaginary plane anywhere in the material we want. Whenever and wherever the downslope gravity force exceeds the friction force, the slab above the plane slides downslope. We say that the material has *failed* along that plane. (The friction force we are dealing with here is the same as what I called the shear strength earlier in the course.)

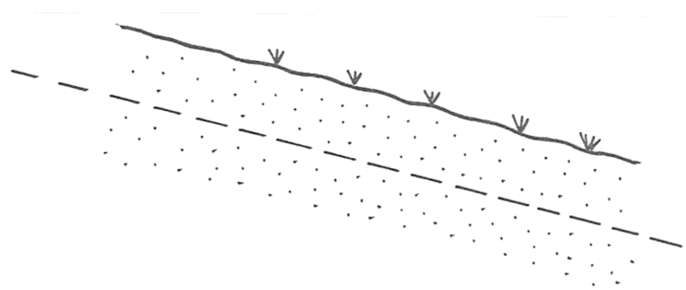

Figure 10-3. The force of gravity on a layer of deformable material on a slope.

BACKGROUND: FRICTION

1 Everybody knows about friction. Life without friction would be unbearable. Friction is essential for locomotion. We would all end up clumped together at the bottoms of local depressions in the land surface, unable to shift our positions in the least.

2 One instructive but technically incomplete definition of ***friction*** is that it's *the force that is generated when one mass of material slides past another mass of material with which it is in contact across a surface*. That definition is a bit too specialized, because it doesn't adequately cover the situation when a continuous medium, like water, undergoes a shearing deformation, as shown in Figure 10-4.

3 To get a handle on shearing deformation, think in terms of taking a thick telephone book and "racking" it so that the pages slide past one another, and then supposing that the shearing motion is continuous throughout, rather than page by page. In such shearing of a continuous medium, there is friction across any imaginary plane through the medium (Figure 10-4B).

4 The phenomena of friction are messy. They involve the details of the surface along which the friction force acts, on scale ranging from macroscopic bumps and corrugations down to the atomic scale. Only recently have physicists begun to inquire deeply into the nature of friction.

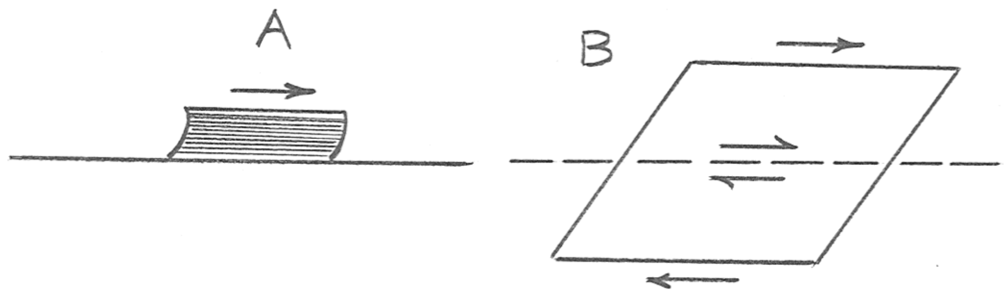

Figure 10-4. A) Shearing a thick telephone book. B) Shearing a continuous medium. The dashed line through the medium represents an imaginary plane of shearing. This single-barb arrows represent the friction force exerted by the material on one side of the plane on the material on the other side.

5 Friction can be dealt with by gathering or subsuming all of the messy phenomena into a single coefficient. (The fancy general term for that kind of thing is called *parameterizing*.) Figure 10-5 shows a slab being made to slide on a horizontal surface by exerting a horizontal force on it. When the slab is moving at constant speed, the force that needs to be exerted on the slab to keep it moving is equal to the friction force between the bottom of the slab and the underlying surface.

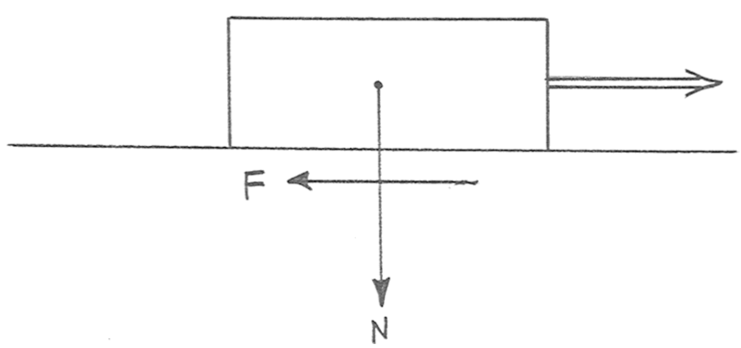

Figure 10-5. Friction on a slab sliding on a horizontal surface.

6 Let the weight of the slab, per unit horizontal area, be N, and the friction force, again per unit area of contact between the slab and the underlying surface, be F (Figure 10-5). These two quantities, N and F, are related by the equation $F = \mu N$, where μ is called the coefficient of sliding friction. It depends only on the nature of the surfaces in contact. Its value is usually less than one. There's an analogous coefficient for ***static friction***, in the situation where the force that tends to move the slab is not yet big enough to cause the slab to move. The coefficient of static friction is generally larger than the coefficient of ***sliding friction***.

2.2.2 If you run the experiment on sliding of a layer of material down your sheet of plywood, you would find that the failure plane (the plane where sliding is located) *is always at the bottom of the layer of material*, whether or not the surface of the plywood is smooth or corrugated. It's easy to see why. The downslope driving force (the weight of the material above a given plane parallel to the plywood sheet) increases with the thickness of the material above that plane, but the coefficient of friction is the same throughout the material. The shear strength of the material (or, what is the same, the static friction) is therefore overcome first at the deepest plane in the layer.

2.2.3 The situation with your sand pile is a bit different. What's happening there is that the slope is oversteepened at the tippity-top of the pile, as a lobe of new material is built. Eventually the lobe fails, and its material slides down the slope.

2.3 The Real World

2.3.1 Now, with all of the foregoing material on the downslope pull of gravity, the nature of friction, and the shear strength of materials as background let's think about *slope failure in nature*. The problem is easy to state. In most places, the land surface has some slope angle. That leads to the possibility of failure and sliding of material downslope. That's the essence of mass wasting. Most of the time, of course, the stuff just sits there on the slope, not moving. (But I will be amending that seemingly obvious statement, in a very important respect, in a later section.) At certain times and places, however, failure occurs, and there is sudden downslope movement, often fast, of some volume of material, often large. What are the factors that determine when and where that will happen? There are two aspects that are important to think about:

- What might cause previously stationary material on a slope to be mobilized?
- How deep below the surface will the failure plane be located?

2.3.2 Let's address the second question first. In nature, with its layer of regolith and weathered rock at the surface and solid bedrock, with its greater strength below, the depth at which failure first occurs depends on the competition between two effects: the tendency, discussed above, for failure to occur as deep as possible; and the general tendency for the shear strength of the material to increase, usually greatly, downward in the transition from regolith to bedrock.

2.3.3 The first question is more difficult to address. Several things, all of them important, might cause failure:

- The material on the slope might be loaded from above, by addition of new layers of material. If there is no concomitant increase in the shear strength of the underlying material, that might lead to failure.
- The slope might be steepened by differential deposition, whereby a layer of newly deposited material is thicker high up on the slope than low down on the slope. That increases the downslope component of the gravity force on the material.
- The base of the slope might be undercut, by stream erosion, for example.
- The shear strength along some plane in the material might be lowered by some effect.

2.3.4 The last of these calls for further comment. The shear strength of a granular material like regolith, as well as a solid but porous material like sedimentary rock, arises from the particle-to-particle forces. If that force can be decreased somehow, the shear strength is lessened. A good way to do that is to increase the pore pressure in the layer. (By ***pore pressure***, I mean *the water pressure of the water in the connected pore spaces in the material*.) Figure 10-6 shows this effect, in a very schematic way. Suppose that there is a layer of relatively permeable material that lies between an overlying layer and an underlying layer of effectively impermeable material. If in some way the fluid pressure in the permeable middle layer is pumped up, that extra pressure tends to lift up the overlying material, thus relieving some of the particle-to-particle forces and lowering the shear strength. That's conducive to failure, and sliding of the overlying layer downslope.

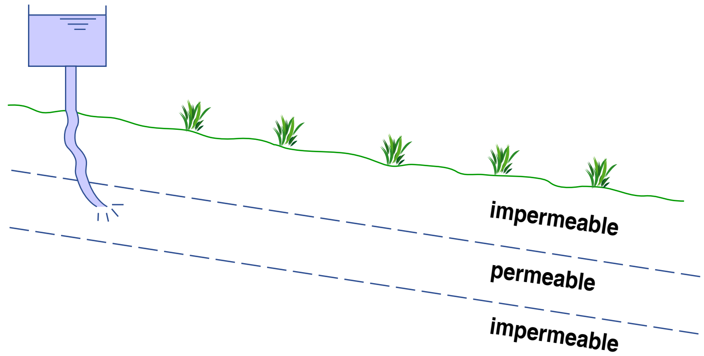

Figure by MIT OCW

Figure 10-6. Increase in pore pressure in a subsurface layer.

3. KINDS OF MASS WASTING

3.1 Enough of theories and generalities. *What kinds of mass-wasting processes are important?* Mass downslope movement of bedrock and/or regolith is a complexly (almost hopelessly) multidimensional phenomenon. Here is a list of some of the factors in this complexity (I'm not pretending that it's a complete list):

slope of the land surface
composition of the surficial material
nature and degree of fracturing of bedrock
degree of weathering of bedrock
rate of downward transition from regolith to bedrock
size, shape, and sorting of regolith particles
porosity
permeability
degree of water saturation of medium
extent of excess pore pressure
fauna and flora
undercutting at base of slope
earthquake vibrations

3.2 Accordingly, *the mode, speed, and volume of downslope mass movements varies enormously*. Below is a list of some types of commonly recognized modes of movement (in alphabetical order). I think that an appropriate adjective in this situation is "bewildering". Many, if not most, of these grade into one another, without clear boundaries.

creep
debris avalanche
debris flow
debris slide
earthflow
gelifluction
lahar
landslide
mudflow
rock fall
rock slide
slump
solifluction
sturzstrom

The most general term in the foregoing list is ***landslide***. That term applies to *all perceptible movement of rock or regolith down a slope*. Two further qualifications are still needed, though:

(1) The adjective "perceptible" leaves out a class of very important mass-wasting processes—*creep* and *solifluction*—that are of great importance but are too slow to stand around and watch.

(2) There's a phenomenon called *debris flows*, whose nature lies somewhere in between what's generally considered to be landslides, on the one hand, and sediment-transporting streamflow (the topic of an earlier chapter) on the other hand.

3.3 Many classifications of types of mass wasting have been proposed. It's generally agreed that the definitive criteria for such classifications are as follows:

- *type of material in motion* (particle size, degree of coherence)
- *mode of motion* (falling, toppling, sliding, flowing)
- *speed of motion*

Rather than trying to present to you various technical classifications, I'm going to deal in the following sections with several of the most important kinds of mass wasting. Given what's said above, it seems natural to do this in the form of three sections: creep and solifluction; landslides; and debris flows.

4. CREEP

4.1 The expressive term ***creep*** is used for *all slow downslope movements of regolith under the pull of gravity that are so slow as to be imperceptible except to observations with long duration* (days to weeks in the case of solifluction; years to decades to centuries in the case of slower creep). It is unspectacular in comparison to the sudden, large-volume, high-speed landslides that make the news reports, and only negligibly destructive (nobody dies from creep!). Its great geological importance arises from its ubiquity.

4.2 We perceive creep to be a continuous process, as over the years we observe the slow downslope movement it engenders, but in fact it's the sum of innumerable small and discrete movements of the slope-mantling regolith. These slow movements are brought about by a number of processes. Classic creep is brought about not by bodily movement of the surface layer above a plane of failure, as discussed at length in earlier sections, but by individual cyclic movements of the material.

4.3 The basic idea is this: particles or small masses of material at or near the surface are lifted upward perpendicular to the surface by any of a number of cyclic processes that involve lifting of material perpendicular to the surface and then lowering of that material in a much more nearly vertical direction. Here's a list of some of the important processes that are thought to contribute to creep:

- wetting and drying
- heating and cooling
- freezing and thawing
- transfer of material to the surface by burrowing organisms, then vertically downward collapse of material overlying the resulting cavities

4.4 All such processes affect only the very near-surface layer of the regolith, generally down to depths of no more than a few meters. The result is a kind of "sawtooth", step-by-step movement of material downslope. Figure 10-7 shows how this effect works in the case of soil particles lifted up by expansion and dropped down again by contraction. Similar figures could be drawn to show the sawtooth effect of other raising-and-lowering processes.

4.5 The sawtooth movement involves a variety of kinds of material:

- individual particles resting directly on the surface
- more extensive masses of the surface layer of regolith

- material brought up from deeper in the profile and deposited on the surface

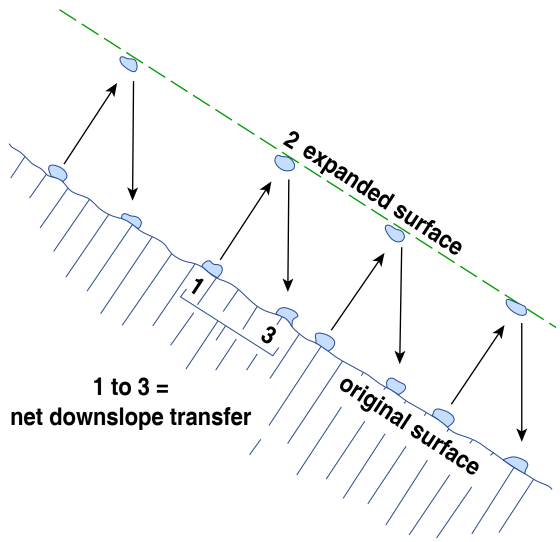

Figure by MIT OCW

Figure 10-7. Sawtooth path of a surface particle caused by expansion and contraction of the soil. (From Bloom, 1998)

4.6 The role of the lowly earthworm is believed to be of special importance in soil creep. (I seem to remember reading once that Darwin himself was aware of the importance of earthworms in soil movement.) The volume of soil processed by earthworms in an ordinary soil in humid temperate regions is staggering. As you must know from your own observations, earthworms work their way to the soil surface at night, leaving those telltale little piles of soil around their holes. In that way there is a net upward movement of soil material normal to the surface. Eventually the tube left behind by the burrowing earthworm collapses, and the tendency is for the collapse to be vertically downward under the pull of gravity. The net result is a sawtooth movement of soil material downslope.

4.7 Figure 10-8 shows common effects of creep. You are not likely to see all of them in one place, but all are clear manifestations of creep.

4.8 ***Solifluction*** is a special kind of creep, by which *a surface layer of water-saturated regolith flows imperceptibly slowly downslope over an impermeable lower layer of some sort*. The impermeability of the lower layer prevents drainage of the overlying soil, causing it to remain for long periods of time in a thickly soupy condition, which predisposes it to downslope flow. It is common in, but not restricted to, high-latitude regions of permafrost, where summer thawing affects only the surface layer, leaving frozen and impermeable material beneath.

Solifluction happens also where there is an impermeable layer of clay-rich "hard pan" beneath a permeable surface layer, and even where there is an impermeable layer of bedrock just below a surface soil zone. In any case, solifluction is promoted by a high percentage of clay in the surface layer. Downslope speeds of solifluction, although still not something you can detect by standing there watching, are much higher than in other kinds of creep: up to some centimeters per day.

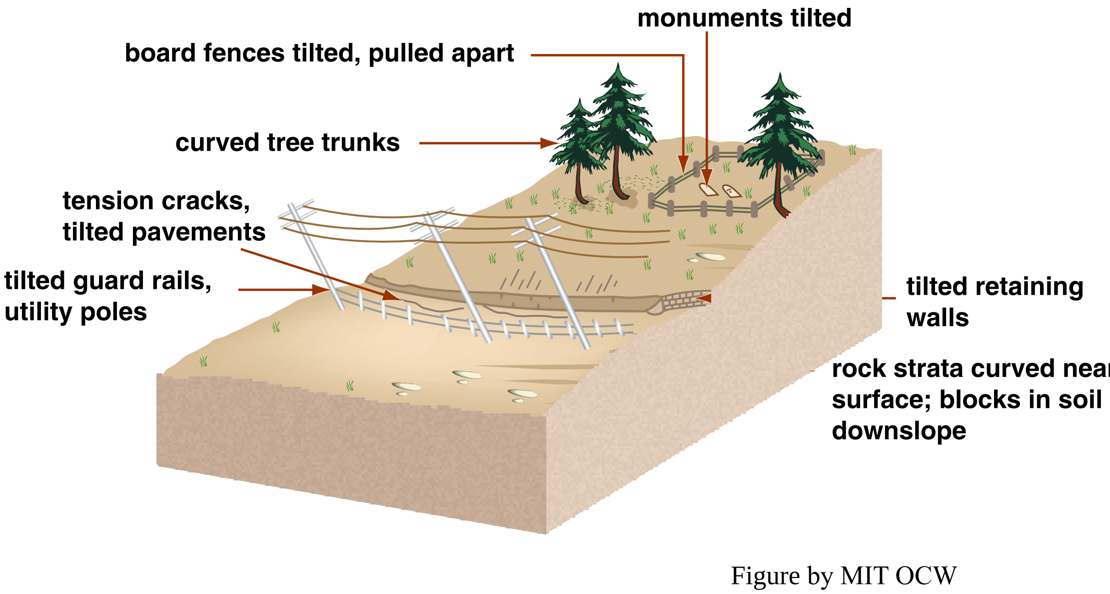

Figure 10-8. Common effects of creep. (From Bloom, 1998)

5. LANDSLIDES

5.1 As noted above, the term *landslide* is used for a variety of downslope movements of rock and regolith. These movements vary greatly in size, speed, and mode of movement. The simplest to understand (see Figure 10-9), and which are dealt with only briefly here, are ***rock falls*** (rapid fall of rock material down a cliff face), ***rock topples*** (downslope collapse of an originally vertical slab of rock that becomes detached along vertical fractures from a main rock mass), and ***rock slides*** (whereby a tabular mass of rock glides down a slope, which is usually underlain by more of the same rock, with planes of weakness parallel to the slope)

5.2 Another characteristic kind of landslide, in which *a large mass of earth or rock material moves downslope along a discrete shear surface of failure*, is called a ***slump*** (see Figure 10-10). The underlying surface is concave upward, and the mass rotates, in the sense of becoming more and more tilted upslope as it moves downslope. As the head of the slump evacuates the original space, a well-defined steep headscarp develops. The downslope segment of the slump, near the toe, commonly flows out onto the preexisting land surface as an earthflow, often with transverse ridges caused by compression as the earthflow feels the frictional resistance of the underlying surface. Slumps like this typically move slowly—not so fast that you can't get out of the way. They are especially common in regions with steep slopes, thick layers of regolith rich in fines, and occasional heavy rains. Many have occurred in coastal central and southern California in historic times. In many cases they have been triggered by careless undercutting of the base of a slope during road construction or other excavations.

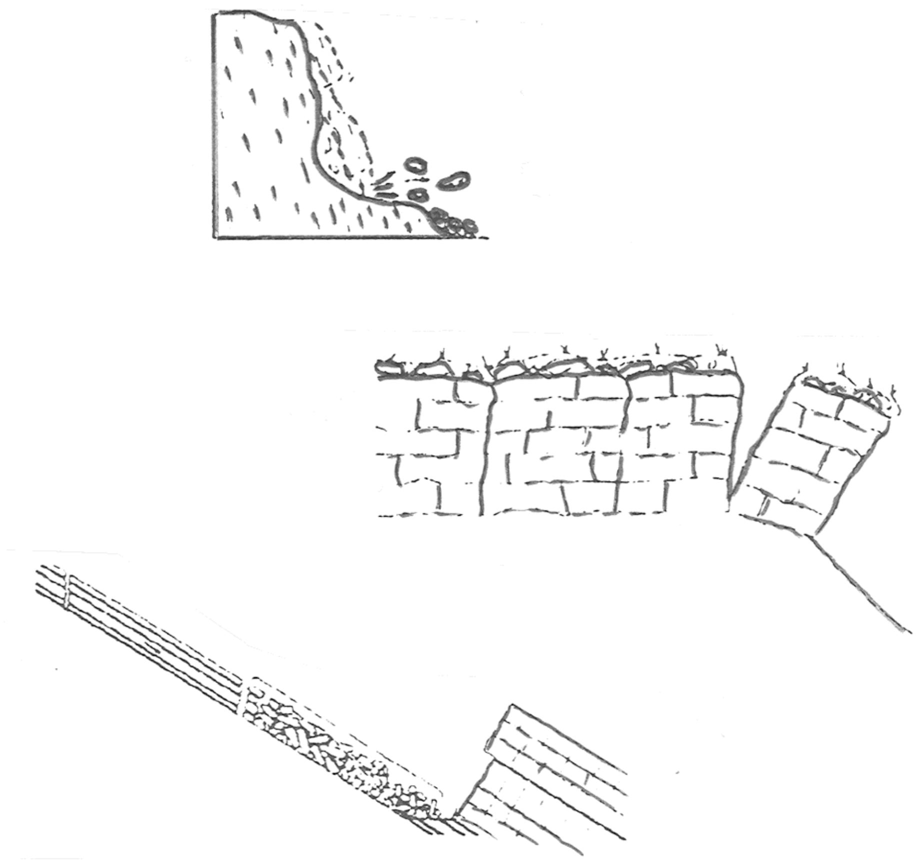

Figure 10-9. Rock falls, rock topples, and rock slides. (After Bloom, 1998)

5.3 The largest and most destructive of landslides originate by failure of enormous masses of partially weathered and strongly fractured rock perched high on a mountain slope. Failure, along a master underlying slip plane, causes the mass of material to accelerate downslope at speeds in excess of a hundred meters per second. Most of the famous landslides in history, and in prehistory as well, have been of this kind. Failure is sometimes triggered by heavy rains, especially in springtime after a thaw, or by undercutting at the base of the slope. Others happen just at random—when the time has come for failure. There may be premonitory slow movement before failure, but prediction is difficult. Volumes of rock material involved can be many cubic kilometers.

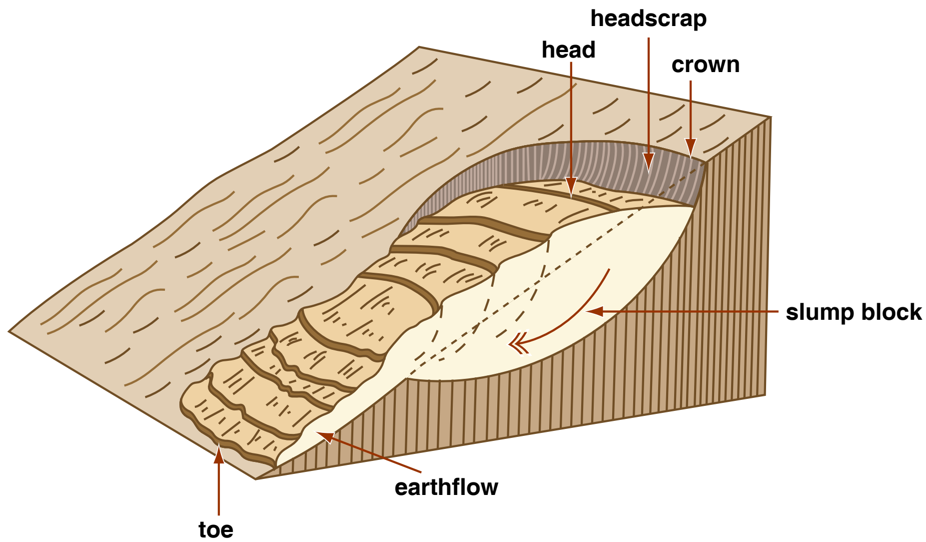

Figure 10-10. A slump. (From Bloom, 1998.)

5.4 In some cases, these large and rapid landslides have run out for long distances beyond the base of the slope down which they traveled, for several kilometers. The mechanism(s) that allow such long runouts over gentle slopes are not entirely clear. For some such landslides, it's been proposed, on good theoretical and observational grounds, that the slide became launched into the air, perhaps when moving over a "lip" of bedrock, and then rode on a cushion of compressed air. Friction at the lower surface would then be far less than in movement over solid materials. (Think in terms of air hockey.) When the cushion of air is finally depleted, by upward flow through the porous and permeable moving material, the slide grinds to a halt.

5.5 As you can imagine, some such landslides have resulted in great loss of life. The worst in recorded history was in Peru in 1970, which involved an enormous volume of rock and ice that moved at speeds of over 300 kilometers per hour and killed as many as 40,000 people. Another famous landslide occurred in northern Italy in 1963, when the entire mountainside, a slab 2 km long, 1.6 km wide, and 250 m thick, flanking the Vaiont Reservoir failed and slid into the reservoir, causing a catastrophic flood that killed more than two thousand people living in the valley below the dam.

5.6 This course is oriented toward what happens on the land surface of the continents, but it's important to point out here that the very largest landslides known have occurred undersea. It's only been in recent years, with the advent of increasingly sophisticated surveying and imaging techniques, that their extent and importance have become clear. The two locales where the largest of such landslides have been observed are on the flanks of the great Hawaiian shield volcanoes (much the greater part of whose volumes lie below sea level) and along the margins of the continents, below the break in slope at the edge of the continental shelf. Some of these are truly enormous, with volumes of thousands of cubic kilometers.

6. DEBRIS FLOWS

6.1 ***Debris flows*** are *concentrated mixtures of water and loose rock and mineral material that flow downslope, usually in a preexisting channel, under the pull of gravity*. Speeds range from a slow walk to a speeding automobile. They differ from ordinary sediment-transporting streamflow in that the motivating force for the downslope movement comes directly from the pull of gravity on the sediment–water mixture. In sediment-transporting streamflow, in contrast, the water flows because of the pull of gravity, and the sediment is moved by the flowing water. (See the earlier chapter on rivers for a lot more material on sediment-transporting stream flow.)

6.2 The classic debris flow has sediment concentrations by volume of over fifty percent—almost to the point at which the sediment particles lock together and prevent movement. It also is characterized by extremely poor sorting of the solid material, from clay-size particles to house-size boulders. Up until recently, it was generally believed that the proportion of mud in a debris flow had to be high. It's know known, especially from laboratory experiments on debris flows, that such flows can happen even at concentrations of muddy material as low as five percent. But below that concentration of mud, debris flows can't happen.

6.3 The classic debris flow is nonturbulent to only weakly turbulent: the mixture moves smoothly and without the vigorous turbulent mixing that's so characteristic of sediment-transporting streamflow. Many debris flows, however—the ones that are relatively "thin" and somewhat more like ordinary streamflow—are clearly turbulent.

6.4 One of the big sticking points in accounting for the existence of debris flows has been *the mechanism (or mechanisms) by which large clasts can remain suspended in the flow in the absence of turbulence*. A number of effects seen to contribute.

• First of all, there's the **buoyancy effect**: the large clasts feel themselves to be immersed in a fluid medium with density much greater than that of clear water, because of the high concentration of finer sediment. The large clasts are therefore only slightly negatively buoyant.

• In flows with relatively high concentrations of clay-mineral particles, what is called **matrix strength**, caused by the electrostatic cohesive forces between clay particles, probably plays a role.

• Finally, the upward **dispersive effect** of strong collisions among clasts as the mixture is sheared is thought to be an important effect.

6.5 Debris flows are of much more than scientific interest. That's because deposition from debris flows is typically by rapid halt of the entire mass rather than incrementally along the path of the flow. Large, fast-moving debris flows can bury entire valleys, demolishing villages and all of their inhabitants, when the moving mass finally comes to rest. Stream valleys on the flanks of active explosive volcanoes in humid regions are especially susceptible, because volcanic ash weathers readily to fine-grained, clay-rich material, and heavy rains can mobilize such material into a massive debris flow, called a ***lahar*** (an Indonesian word).

READINGS

Bloom, A.L., Geomorphology; A Systematic Analysis of Late Cenozoic Landforms, Third Edition. Prentice Hall, 482 p. (Chapter 9)

Easterbrook, D.J., 1999, Surface Processes and Landforms, Second Edition. Prentice hall, 546 p. (Chapter 4)