Chapter 8
Landslides

Introduction

Landslides occur in a wide variety of settings, including subduction complexes, volcanic arcs, transform faults, and intraplate settings like Hawaii. They also are common anywhere on the Earth's surface where steep topographic slopes exist or where weak water saturated material lies on slopes ranging from a fraction to many degrees of inclination. Under such conditions, the down slope movement of material is commonly referred to as mass wasting. In the following sections, I first define this phenomenon in more detail, and then review the role that gravity plays in moving material down slope. I then cover the various types of landslides, and then end this chapter by looking at two important case studies.

Mass Wasting and Landslides

Mass wasting refers to the down slope movement of Earth materials such as regolith or solid rock under the influence of gravity. **Regolith** is a term used to refer to all of the materials lying between unweathered rock below and the Earth's surface above. It therefore includes weathered rock, soils, and unconsolidated deposits derived from flowing water, ice (glaciers), and wind. When such material rests on horizontal surfaces, then it is relatively stable. However, if it rests on an inclined or sloped surface, then the degree to which the inclined or sloped surface varies from the horizontal, determines its stability. In such settings the resistance of the regolith to down slope motion is dependent upon its cohesiveness and its frictional resistance to motion. In addition, plant roots tend to bind the regolith, and therefore act as a stabilizing agent.

Gravity

Shown in Figure 1A is a large boulder resting on a horizontal surface. In such a setting, the only force acting on the boulder is that due to gravity. As you might recall from high school physics, a force is a vector and therefore has both direction and magnitude. In Figure 1A, the gravitational force is depicted by the vertical black arrow pointing downward. The length of this arrow is the magnitude of the gravitational force. If the surface on which the boulder rests slopes at some angle other than zero, then the gravitational force will consist of two components, one acting parallel to the sloping surface (see blue arrow in Figures 1B, 1C, and 1D), and the other acting orthogonally or normal to it (see red arrow in Figures 1B, 1C, and 1D). The former is the tangential while the latter is the normal component of gravity. The **tangential component** is that part of the gravitational force that tends to pull the boulder down the slanted surface. In contrast, the **normal component** is that part of the gravitational force that tends to hold the boulder on to the inclined surface.

If the surface on which the boulder rests makes an angle of say 40^{o} relative to the horizontal, then the normal component of gravity will be greater than the tangential component, and the boulder likely will not move down the slope (Figure 1B). However, if the angle of inclination is higher, say 50^{o}, then the magnitude of the tangential component will exceed the normal component, and thus the likelihood that the boulder will slide down the inclined surface will be greatly increased (Figure 1C and 1D).

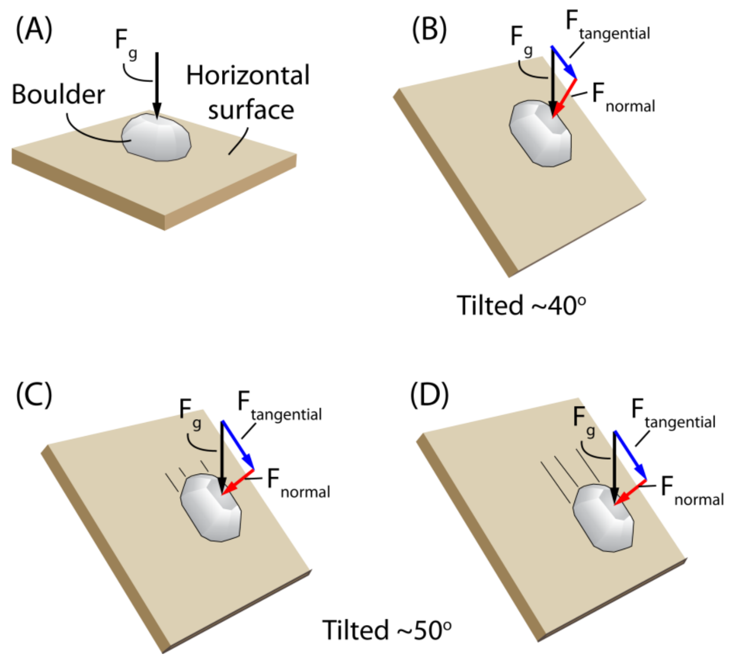

Figure 1. The effects of gravity. See text for explanation.

As mentioned in the introductory comments, the physical properties of material that rests on, or directly underlies, a segment of the Earth's surface that is steeply inclined play an important role in whether or not they will slide down such slopes under the influence of the tangential component of gravity. For example, if the Earth's surface is underlain directly by solid fracture-free rock, then it can form very steep slopes without any material breaking free and sliding downward. At the other end of the spectrum, if the solid fracture-free rock surface is overlain by loose granular materials (e.g., the regolith), then such material will slide down slopes with even small inclinations. Lying between these two extremes is a wide variety of materials with different physical properties that will determine if they will move under the tangential component of gravity or not. Some of this material will break into coherent blocks that will fall freely through the air prior to bouncing or rolling down hill, whereas other material when saturated with water will flow with the consistency of wet cement down slope. All of these processes and their resulting deposits are often lumped under the general heading of **landslides** which D.J. Varnes (1958) defined as *the downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials*. The moving mass proceeds down slope by falling, sliding, spreading, flowing, or some combination of these three processes. The movement of falls, slides, spreads, and most flows are perceptible to the human eye, while creep and solifluction occur so slowly that the human eye can't detect the down slope motion characteristic of these two processes.

A landslide is classified on the basis of (1) the type of material that existed prior to the landslide and (2) the type of movement that dominates during the landslide. The types of material that might exist prior to a landslide are rock, soil, earth, mud, and debris.

Rock is defined as any intact, hard, and firm mass that existed in its natural place prior to the landslide. Examples include igneous, metamorphic, and lithified sedimentary rocks. At the other end of the spectrum is **soil,** an aggregate of minerals and rock fragments plus or minus organic material that formed from the in situ weathering of rock or sediments. In a soil, pores or open voids between the minerals and rock fragments are often filled with gases or water.

Material defined as **earth** is composed of ~80% or more particles smaller than 2 mm (the upper size limit of sand) while **mud** is composed of 80% or more particles smaller than about 0.06 mm (the upper limit of silt). Finally, **debris** contains 20% to 80% particles larger than 2 mm, while the remainder is generally less than 2 mm.

The four general classes of movement during any given landslide are fall, slide, spread, and flow. Hence, to classify a landslide you first determine the type of material that existed prior to the landslide and then attach to that name the class of movement. Using such a scheme, a *rock fall* is a landslide that involved intact, hard, and firm material that fell down slope while an *earthflow* is a landslide that involved the flowage of earth material down slope.

A **complex landslide** commonly involves two or more of the classes fall, slide, spread, or flow. For example, in its lower parts, a *rotational slide* commonly transforms into an *earthflow*. Hence, such a landslide would be classified as a *complex rotational slide-earthflow*.

Falls

Rock falls are produced when solid material or soil become detached from a steep slope and then fall freely for some distance or bounce and roll down the slope (Figures 2 and 3).

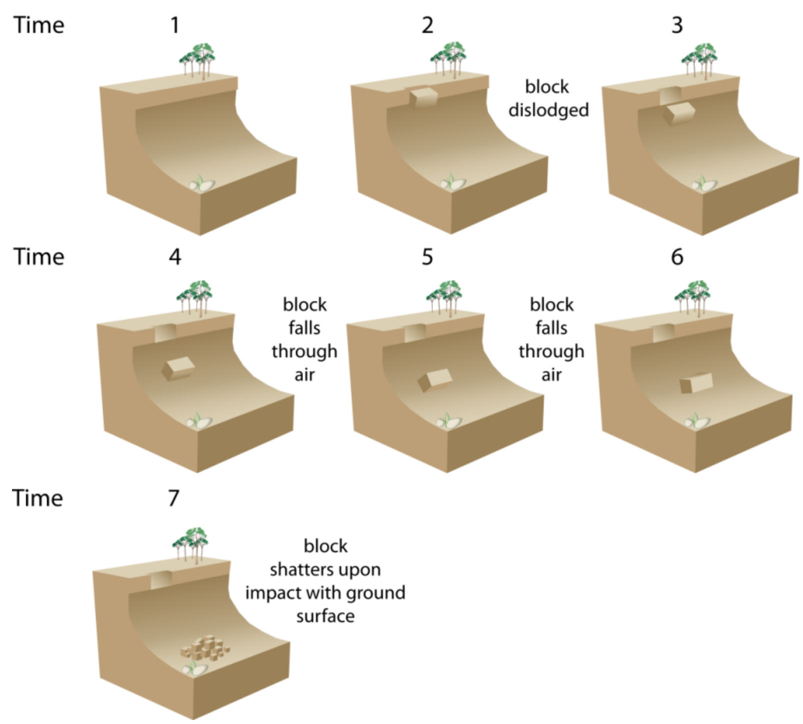

Figure 2. Time sequence for development of air fall. At time 2 block is dislodged from overhang. It then falls freely through the atmosphere during time intervals 3 through 6. Between time intervals 6 and 7 it impacts ground and shatters.

Detachment of solid blocks or soils along such steep slopes occurs as a result of freeze-thaw, ground shaking during earthquakes, saturation by water during torrential rainstorms, or weakening by the growth of plant roots. **Topples** are rock falls that involve the forward rotation of a detached block above a pivotal point located in the lower part of the detached material (Figure 4). Common everyday evidence of a rock fall or topple is a road littered with rock debris derived from an adjacent steep slope (Figure 5).

Figure 3. Photograph taken from Royal Arches Route climb from across the canyon by rock climber Lloyd DeForrest while dangling on the rope 2000 feet above the valley floor. Source: USGS Landslide Photo Collection.

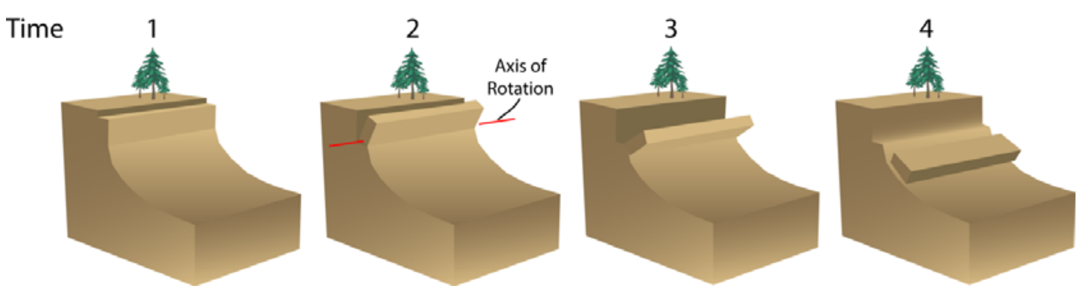

Figure 4. A topple is a rock fall in which the dislodged block rotates about an axis in its lower part (time 2) as it pitches forward (times 2 and 3) prior to falling (time 4).

Figure 5. Results of rock fall, Truckee River, California. Large boulders and debris along road were dislodged from steep slope in foreground during an earthquake on September 12, 1966. They fell and bounced down the slope shattering on impact with the road. Photograph by R. Kachadoorian, United States Geological Survey.

Slides

Slides, a synonymous term is **slumps,** form when a coherent mass of regolith or bedrock breaks free and then slides down slope along either a planar or curved surface. The geometry of the detachment or rupture surface and the degree to which the sliding material remains coherent determines the type of slide.

Translational: If the detached landmass slides along a relatively planar surface, then the resulting slump is called translational (Figure 6). Relatively common planar surfaces of failure are joints or bedding planes. If the material in the toe region liquefies, then the down slope

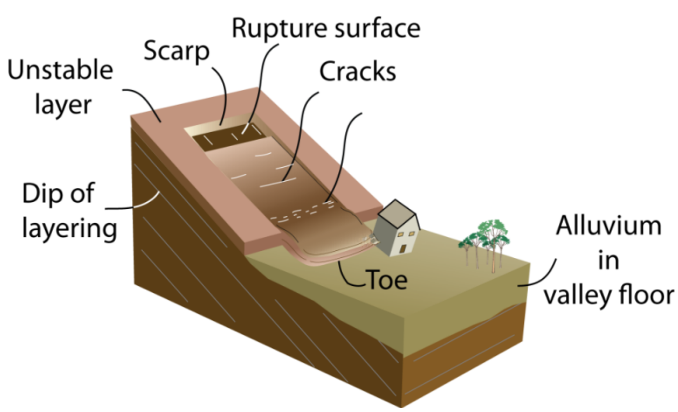

Figure 6. Note that the slide mass broke free and then slid down slope along a bedding plane and that the toe region is an earthflow. Cracks that form perpendicular to the long dimension of the translational slide are extensional.

end of a translational slide may turn into an earthflow.

A **block slump** is a translational slump in which the detached landmass consists of a single or a few closely related units that move down slope as a relatively coherent mass (Figure 7).

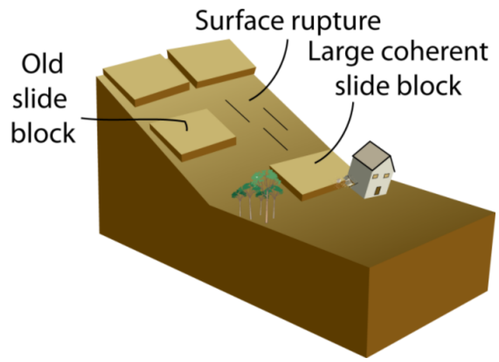

Figure 7. Block slump impacting and destroying house.

Rotational: When a coherent mass of regolith breaks free from a slope along a curved slip surface, the resulting slump is called rotational (Figures 8 and 9). As the coherent mass moves down slope along the curved slip surface it rotates downward leaving at its head a crescent shaped scarp or **crown**. At the opposite end of the slump, in the **toe** region, material may lose coherence and flow slowly down slope as an earthflow. In such cases, the slide is a complex rotational slump-earthflow.

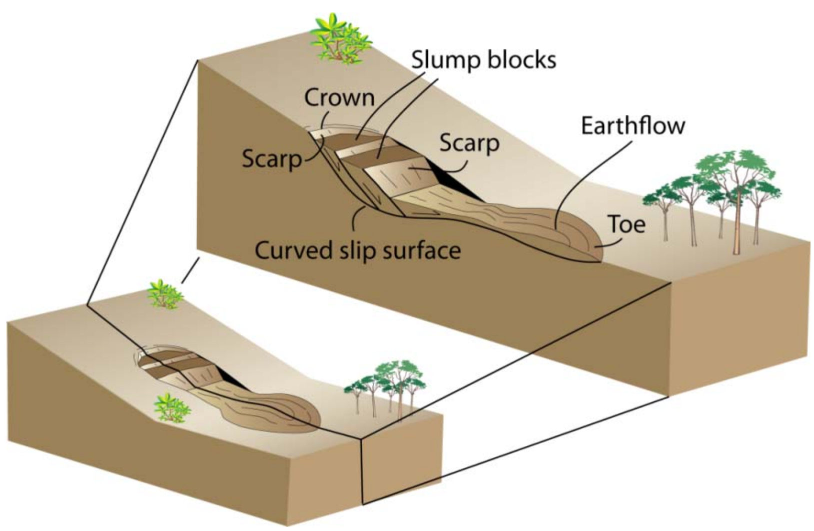

Figure 8. A complex rotational slump-earthflow consists of a rotational slump with an earthflow in its lower toe region.

Figure 9. Photograph from United States Geological Survey. During the March 27, 1964 Alaskan earthquake, a large slump occurred in the Turnagain Heights area of Anchorage. Note the various houses for scale. The various slump blocks slide along the various scarps from upper right to lower left and rotated downward in a clockwise sense.

Spreads

Lateral spreads commonly occur on very gentle or flat slopes. Failure occurs as a result of liquefaction, the process by which saturated, loose, cohesionless sediments are transformed from a solid into a liquid state. Such changes in state can be induced by ground shaking during earthquakes. If liquefaction occurs within a layer overlain by more coherent materials, then the upper layers may fracture and then subside, translate, rotate, disintegrate, or liquefy and flow (Figure 10).

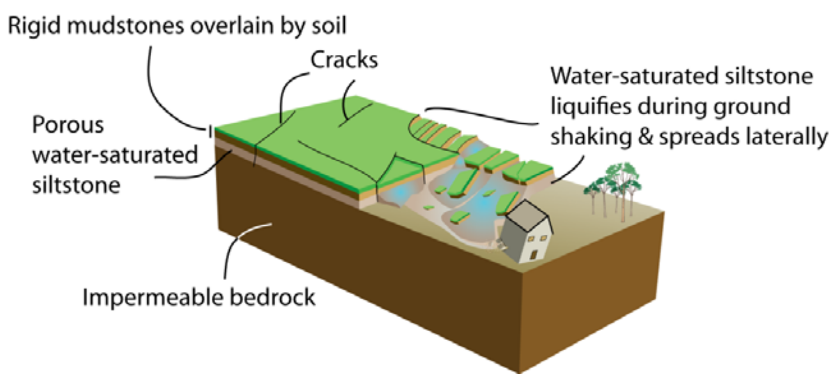

Figure 10. Cut away view of a lateral spread. Green and dark brown layers in upper part of illustration are rigid firm mudstones. Underlying these two uppermost layers is an interval of water-saturated siltstone that rests on impermeable bedrock. During an earthquake ground shaking liquefies a portion of the water-saturated siltstone and it spreads laterally down slopes and toward cliff faces.

Flows

***Earthflows*:** Water-saturated fine-grained slope material that liquefies and then runs out, leaving a bowl-shaped depression on the sloping land surface are called earthflows (Figure 11). As the earthflow moves down slope it remains covered with vegetation. At the head of the bowl-shaped depression, where the material in the earthflow pulled away from the slope, a scarp is commonly present. Lying between the bowl-shaped depression and the area of deposition is the main track, the area where the earthflow traveled from the source area to the depositional site. Dependent upon how much water they contain, earthflows travel at various speeds ranging from 0.17 to 20 kilometers per hour (0.11 to 12.4 miles per hour). The greater the water content, the faster they travel. However, earthflows are generally slower than mudflows (see below).

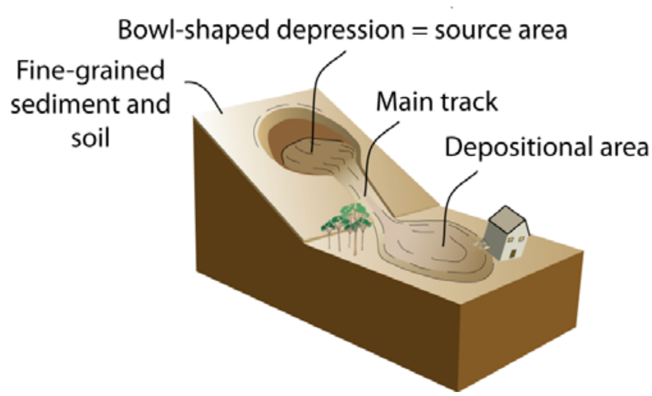

Figure 11. Earthflows occur when water-saturated fine-grained material (~80% of the particles are less than about 2.0 mm in size) lying on a slope liquefies. The liquefied material then flows down slope leaving behind a bowl-shaped depression.

The deposit resulting from an earthflow is elongated and composed of more than 80% fine-grained sediment and/or soil particles finer grained than ~2.0 mm. In plan view (i.e., looking from the sky vertically down on the earthflow system), the bowl-shaped depression and site of deposition commonly form the outline of an hour-glass (Figure 11).

***Debris flows*:** Following intense torrential rainfall, or during melting of large amounts of snow or ice, lose regolith on steep slopes may become water-saturated and unstable, and as a result, give way flowing down slope accumulating in and moving down ravines and other natural channels as a debris flow (Figure 12). Such flows are said to have the consistency of wet cement. In debris flows grain size varies considerably, ranging from less than ~0.004 mm to over ~256 mm (Figure 13). In such a water-saturated mixture, *grains larger than sand (~2.0 mm) make up between 20% - 80% of the solid material*. Debris flows can reach speeds up to ~56 kilometers per hour (~35 miles per hour).

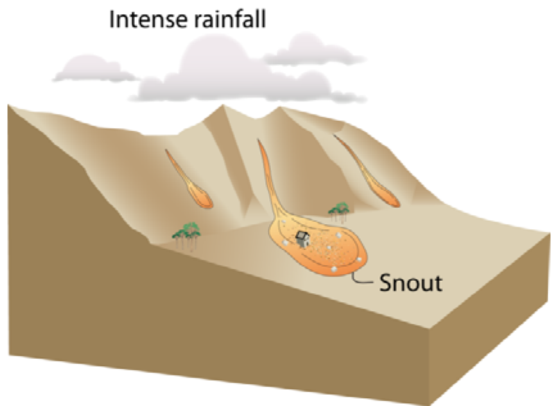

Figure 12. Debris flows commonly occur following heavy rainfall.

Figure 13. Snout of debris flow, San Bernardino Mountains, California. Note the many blocks larger than 256 mm, the approximate diameter of a basketball, and the wide range in size of material incorporated into the flow. Photograph by D. Morton, United States Geological Survey.

Mudflows: If slopes are covered by water-saturated soils or fine-grained sedimentary deposits, then following an intense rainfall or the melting of large amounts of snow and ice, such material may become liquefied resulting in a mudflow (Figures 14). Of *the solid material incorporated into such flows more than 80% are less than silt size (~0.06 mm)*. Mudflows are generally faster than earthflows and are finer grained than debris flows (Figure 14).

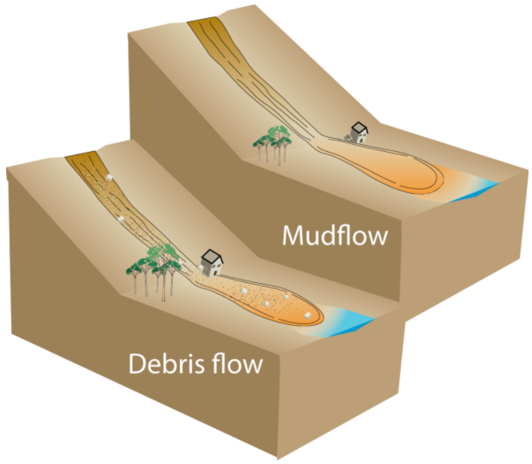

Figure 14. The major difference between a mudflow and a debris flow is the size of the material carried by the flow. As shown in this illustration, the general size of particles in a debris flow is significantly larger than the size of particles in a mudflow. Both types of flows commonly follow and plug up stream channels.

Creep

The imperceptible slow and steady down slope movement of the regolith is defined as creep. Though you can't perceive such motion with the naked eye, curved or bent segments of tree trunks (Figure 15), restraining walls, fences, roads, or railroad tracks (Figure 16) along with the down slope tilting of layered rocks (Figure 17) and tilted telephone poles, all attest to its existence.

Figure 15. Bent tree trunks as a result of down slope creep. Photograph by G.K. Gilbert 1969, United States Geological Survey.

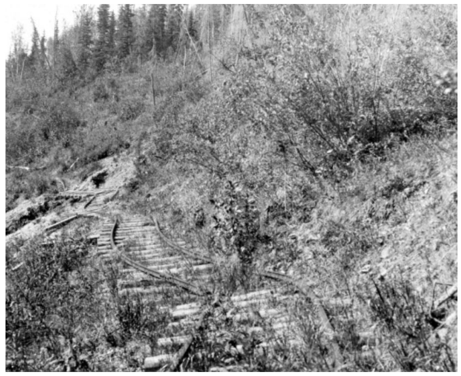

Figure 16. Effects of hillside creep on railroad tracks. Photograph by W.W. Atwood, United States Geological Survey.

Figure 17. Creep in shale. Photo by G.W. Stose, United States Geological Survey.

Solifluction

Permafrost is soil that remains frozen for at least two consecutive years. During the summer, the surface layer melts creating a water-saturated mobile layer that then moves slowly down slope as it slides over the still frozen and impermeable underlying regolith (Figure 18). In areas of permafrost, this slow imperceptible motion down slope is referred to as solifluction.

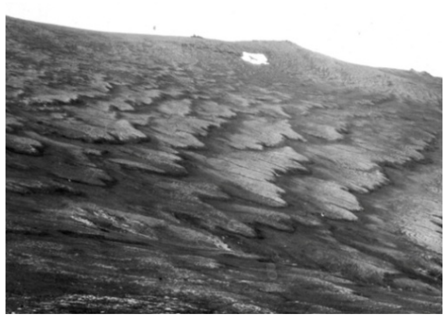

Figure 18. Solifluction lobes Seward Peninsula, Alaska. Photograph by P.S. Smith, United States Geological Survey.

Summary

Landslides are the result of the mass wasting of the Earth's surface. Down slope movement is the result of gravity and/or its tangential component often acting in conjunction with a change in the physical state of the acted upon material. Let's take a look at two relatively recent examples that exemplify well why we should know something about this important and ubiquitous process.

Two Case Studies

The Mount Soledad Landside

On Wednesday morning, just before 9:00 am, October 3rd, 2007 a large mass of the slope lying between Soledad Mountain Road and Desert View Drive, La Jolla, California detached and began sliding down slope (Figures 19). As a result, in the area of the slide, gas mains, water lines, and sewer lines broke. Because of extensive damage, nine houses were red-tagged. The costs were estimated at $26 million for public works such as broken sewer and water mains and a sunken section of Soledad Mountain Road, and $22 million for private property losses. Should the residence involved in the Mount Soledad slide have been surprised?

Figure 19. Aerial view of Mount Soledad landslide. Photograph courtesy M. Hart.

Before answering this question let's review some of the geology and history of the Mount Soledad area.

(1) Much of the Mount Soledad area is underlain by the middle Eocene Ardath Shale, a formation that is known to be susceptible to landslides (Figure 20).

(2) The geologic map for San Diego shows many ancient landslide deposits in the Mount Soledad area. In fact, the October 2007 landslide occurred in an area where geologists had mapped several ancient landslides (Figure 20).

(3) The Mount Soledad area is transected by the Rose Canyon - Country Club fault system (Figure 20), first recognized in the 1970s. This fault system was not recognized in the 1950s and 1960s when many of the houses were built in the Mount Soledad area. Nevertheless, the October 2007 landslide occurred along the trace of the Country Club fault, as did several other ancient landslides shown on the geologic map of the Mount Soledad area (Figure 20).

(4) A landslide destroyed 7 homes under construction in December 1961, while additional landslides occurred in 1990 and 1994.

In short, there is a long history of landslide activity in the Mount Soledad area, and the fact that another one occurred is not at all surprising. Do you think that still others will occur sometime in the future?

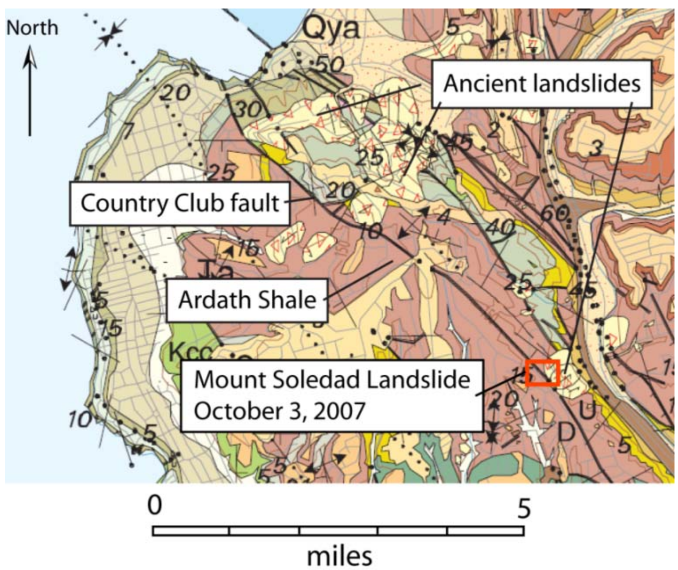

Figure 20. Geologic map of Mount Soledad area, San Diego, California.

The La Conchita Landslide

La Conchita is located along the Pacific Coast of California about midway between Ventura and Santa Barbara (Figure 21). On March 4, 1995 at 2:03 pm, a section of the hills in back of La Conchita dropped downward and flowed slowly toward the Pacific Ocean (Figure 22). This particular mass-wasting event has been classified as a *complex slump-earthflow*. The scarp at the head of the 1995 slump is clearly visible in Figure 22. The lower part of the landslide that tuned into an earthflow is that part encroaching on the homes in the lower half of the photograph. No one was killed during the March 4 event, but the earthflow destroyed or severely damaged 9 houses.

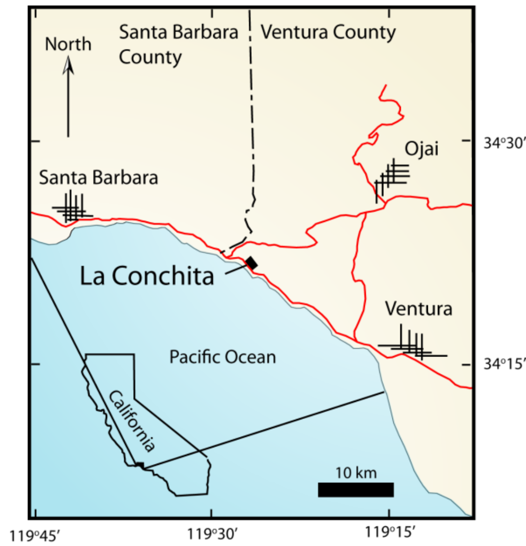

Figure 21. Location of La Conchita midway between Ventura and Santa Barbara, California.

Figure 22. La Conchita landslide, March 4, 1995. Photograph from United States Geological Survey. See text for discussion of Rincon slide.

On January 10, 2005 at 12:30 pm another massive landslide occurred. This event did not involve new material, but remobilized the southeastern portion of the old 1995 landslide (Figure 23). This horrifying experience was caught on video by a TV camera crew. During the

Figure 23. La Conchita following the 2005 landslide. The 2005 landslide reactivated the SE portion of the 1995 landslide. Photograph courtesy United States Geological Survey.

January 10 event, the slide material was mobilized nearly instantaneously into a highly fluid, and rapidly moving debris flow that ultimately buried four blocks of the town in over ~9.1 meters (~30 feet) of debris. Ten people were killed and 14 were injured. Of the 166 homes in La Conchita, 15 were destroyed and 16 were tagged as uninhabitable.

Both the March 4 and January 10 landslides occurred following intense long periods of rainfalls that elevated ground water tables and weakened the cliffs above La Conchita. For example, the 2005 landslide occurred at the end of a 15-day period that produced record and near record amounts of rainfall in southern California while the 1995 event occurred during an extraordinarily wet year.

Investigations by Larry Gurrola and other scientists at UC Santa Barbara indicate that the March 4 and January 10 events are small parts of a much larger ancient landslide called the Rincon Mountain slide. The main scarp or this larger ancient landslide is clearly visible in the photograph shown in Figure 22.

According to Gurrola, "landslides similar or larger than the 1995 and 2005 events may occur next year or in coming decades, during or shortly after intense rain falls". If the inhabitants had recognized the geologic setting of La Conchita would they still have built their homes on a narrow coastal strip adjacent to a steep slope composed of soft weak sediment and clear evidence of an ancient landslide scarp? Is it safe to continue living in La Conchita?

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Maps

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