Chapter 15 Mass Wasting

Learning Objectives

After reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Explain how slope stability is related to slope angle
- Summarize some of the factors that influence the strength of materials on slopes, including type of rock, presence and orientation of planes of weakness such as bedding or fractures, type of unconsolidated material, and the effects of water
- Explain what types of events can trigger mass wasting
- Summarize the types of motion that can happen during mass wasting
- Describe the main types of mass wasting—creep, slump, translational slide, rotational slide, fall, and debris flow or mudflow—in terms of the types of materials involved, the type of motion, and the likely rates of motion
- Explain what steps we can take to delay mass wasting, and why we cannot prevent it permanently
- Describe some of the measures that can be taken to mitigate the risks associated with mass wasting

Figure 15.0.1 The site of the 1965 Hope Slide as seen in 2014. The initial failure is thought to have taken place along the foliation planes and sill within the area shown in the inset.

Early in the morning on January 9, 1965, 47 million cubic metres of rock broke away from the steep upper slopes of Johnson Peak (16 kilometres southeast of Hope) and roared 2,000 metres down the mountain, gouging out the contents of a small lake at the bottom, and continuing a few hundred metres up the other side (Figure 15.0.1). Four people, who had been stopped on the highway by a snow avalanche, were killed. Many more might have become victims, except that a Greyhound bus driver, en route to Vancouver, turned his bus around on seeing the avalanche. The rock failed along weakened foliation planes of the metamorphic rock on Johnson Peak, in an area that had been eroded into a steep slope by glacial ice. There is no evidence that it was triggered by any specific event, and there was no warning that it was about to happen. Even if there had been warning, nothing could have been done to prevent it. There are hundreds of similar situations throughout British Columbia.

What can we learn from the Hope Slide? In general, we cannot prevent most mass wasting, and significant effort is required if an event is to be predicted with any level of certainty. Understanding the geology is critical to understanding mass wasting. Although failures are inevitable in a region with steep slopes, larger ones happen less frequently than smaller ones, and the consequences vary depending on the downslope conditions, such as the presence of people, buildings, roads, or fish-bearing streams.

An important reason for learning about mass wasting is to understand the nature of the materials that fail, and how and why they fail so that we can minimize risks from similar events in the future. For this reason, we need to be able to classify mass-wasting events, and we need to know the terms that geologists, engineers, and others use to communicate about them.

Mass wasting, which is synonymous with “slope failure,” is the failure and downslope movement of rock or unconsolidated materials in response to gravity. The term “landslide” is almost synonymous with mass wasting, but not quite because some people reserve “landslide” for relatively rapid slope failures, while others do not. Because of that ambiguity, we will avoid the use of “landslide” in this textbook.

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15.1 Factors That Control Slope Stability

Mass wasting happens because tectonic processes have created uplift. Erosion, driven by gravity, is the inevitable response to that uplift, and various types of erosion, including mass wasting, have created slopes in the uplifted regions. Slope stability is ultimately determined by two factors: the angle of the slope and the strength of the materials on it.

Figure 15.2 shows a block of rock situated on a rock slope. The block is being pulled toward Earth's centre (vertically down) by gravity. We can split the vertical gravitational force into two components relative to the slope: one pushing the block down the slope (the **shear force**), and the other pushing into the slope (the **normal force**). The shear force, which wants to push the block down the slope, has to overcome the strength of the connection between the block and the slope, which may be quite weak if the block has split away from the main body of rock, or may be very strong if the block is still a part of the rock. This is the **shear strength**, and in Figure 15.1.1a, it is greater than the shear force, so the block should not move. In Figure 15.1.1b the slope is steeper and the shear force is approximately equal to the shear strength. The block may or may not move under these circumstances. In Figure 15.1.1c, the slope is steeper still, so the shear force is considerably greater than the shear strength, and the block will very likely move.

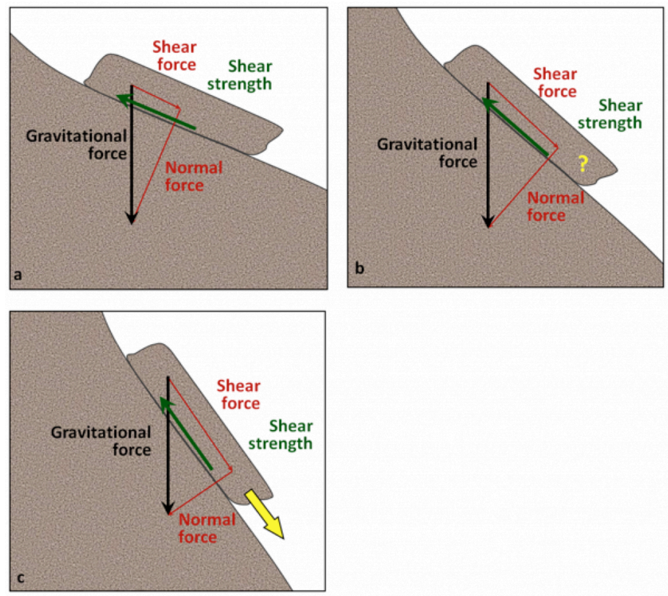

Figure 15.1.1 Differences in the shear and normal components of the gravitational force on slopes with differing steepness. The gravitational force is the same in all three cases. In (a) the shear force is substantially less than the shear strength, so the block should be stable. In (b) the shear force and shear strength are about equal, so the block may or may not move. In (c) the shear force is substantially greater than the shear strength, so the block is very likely to move.

As already noted, slopes are created by uplift followed by erosion. In areas with relatively recent uplift (such as most of British Columbia and the western part of Alberta), slopes tend to be quite steep. This is especially true where glaciation has taken place because glaciers in mountainous terrain create steep-sided valleys. In areas without recent uplift (such as central Canada), slopes are less steep because hundreds of millions of years of erosion (including mass wasting) has made them that way. However, as we'll see, some mass wasting can happen even on relatively gentle slopes.

The strength of the materials on slopes can vary widely. Solid rocks tend to be strong, but there is a very wide range of rock strength. If we consider just the strength of the rocks, and ignore issues like fracturing and layering, then most crystalline rocks—like granite, basalt, or gneiss—are very strong, while some metamorphic rocks—like schist—are moderately strong. Sedimentary rocks have variable strength. Dolostone and some limestone are strong, most sandstone and conglomerate are moderately strong, and some sandstone and all mudstones are quite weak.

Fractures, metamorphic foliation, or bedding can significantly reduce the strength of a body of rock, and in the context of mass wasting, this is most critical if the planes of weakness are parallel to the slope and least critical if they are perpendicular to the slope. This is illustrated in Figure 15.1.2. At locations A and B the bedding is nearly perpendicular to the slope and the situation is relatively stable. At location D the bedding is nearly parallel to the slope and the situation is quite unstable. At location C the bedding is nearly horizontal and the stability is intermediate between the other two extremes.

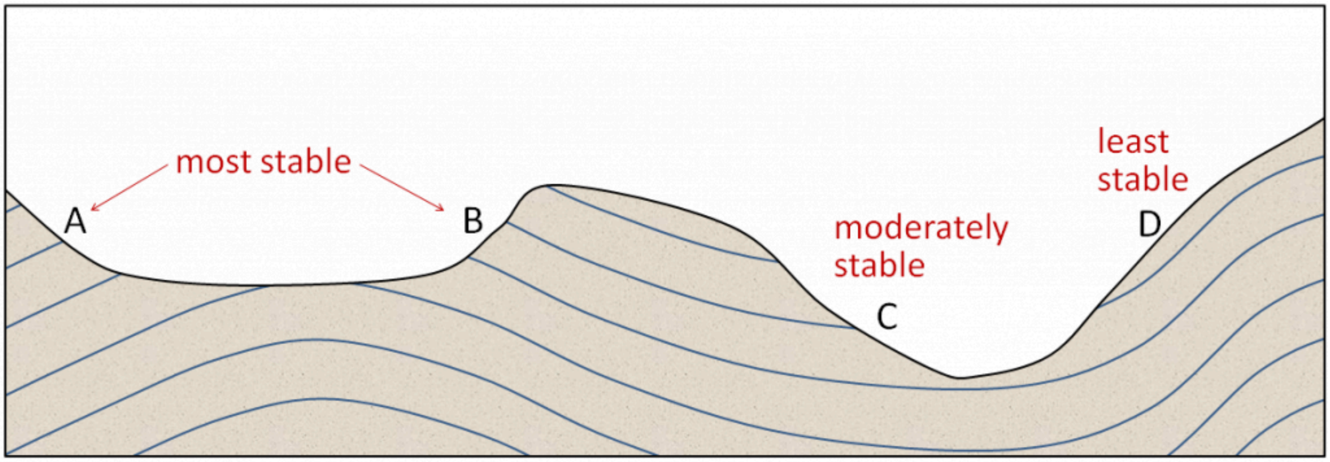

Figure 15.1.2 Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations.

Internal variations in the composition and structure of rocks can significantly affect their strength. Schist, for example, may have layers that are rich in sheet silicates (mica or chlorite) and these will tend to be weaker than other layers. Some minerals tend to be more susceptible to weathering than others, and the weathered products are commonly quite weak (e.g., the clay formed from feldspar). The side of Johnson Peak that failed in 1965 (Hope Slide) is made up of chlorite schist (metamorphosed sea-floor basalt) that has feldspar-bearing sills within it (they are evident within the inset area of Figure 15.0.1). The foliation and the sills are parallel to the steep slope. The schist is relatively weak to begin with, and the feldspar in the sills, which has been altered to clay, makes it even weaker.

Unconsolidated sediments are generally weaker than sedimentary rocks because they are not cemented and, in most cases, have not been significantly compressed by overlying materials. This binding property of sediment is sometimes referred to as *cohesion*. Sand and silt tend to be particularly weak, clay is generally a little stronger, and sand mixed with clay can be stronger still. The deposits that make up the cliffs at Point Grey in Vancouver include sand, silt, and clay overlain by sand. As shown in Figure 15.1.3 (left) the finer deposits are relatively strong (they maintain a steep slope), while the overlying sand is relatively weak, and has a shallower slope that has recently failed. Glacial till—typically a mixture of clay, silt, sand, gravel, and larger clasts—forms and is compressed beneath tens to thousands of metres of glacial ice so it can be as strong as some sedimentary rock (Figure 15.1.3, right).

Figure 15.1.3 Left: Glacial outwash deposits at Point Grey, in Vancouver. The dark lower layer is made up of sand, silt, and clay. The light upper layer is well-sorted sand. Right: Glacial till on Quadra Island, B.C. The till is strong enough to have formed a near-vertical slope.

Apart from the type of material on a slope, the amount of water that the material contains is the most important factor controlling its strength. This is especially true for unconsolidated materials, like those shown in Figure 15.1.3, but it also applies to bodies of rock. Granular sediments, like the sand at Point Grey, have lots of spaces between the grains. Those spaces may be completely dry (filled only with air); or moist (often meaning that some spaces are water filled, some grains have a film of water around them, and small amounts of water are present where grains are touching each other); or completely saturated (Figure 15.1.4). Unconsolidated sediments tend to be strongest when they are moist because the small amounts of water at the grain boundaries hold the grains together with surface tension. Dry sediments are held together only by the friction between grains, and if they are well sorted or well rounded, or both, that cohesion is weak. Saturated sediments tend to be the weakest of all because the large amount of water actually pushes the grains apart, reducing the mount friction between grains. This is especially true if the water is under pressure.

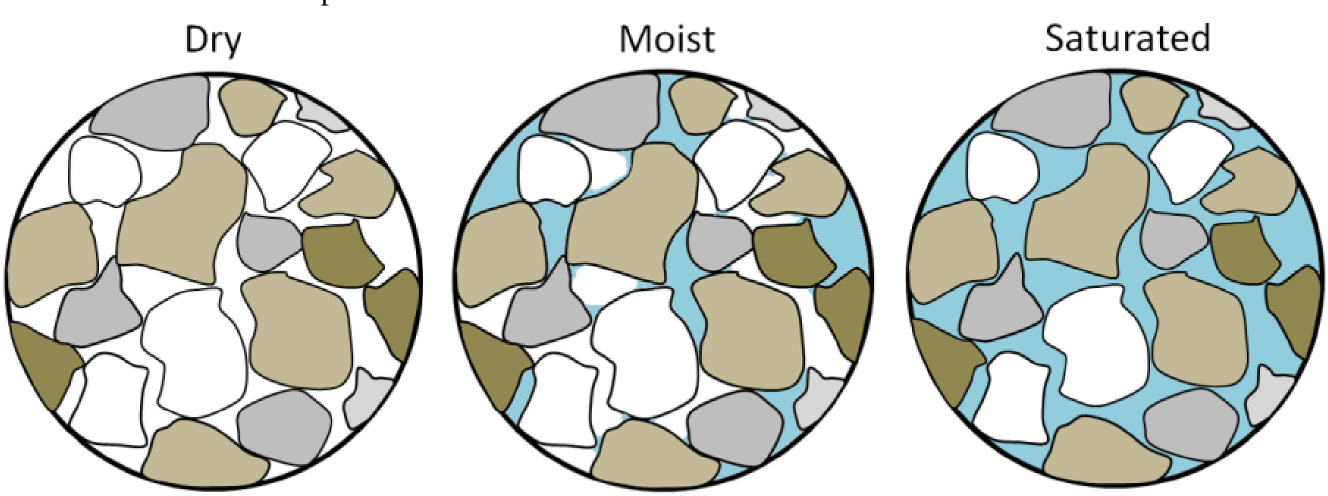

Figure 15.1.4 Depiction of dry, moist, and saturated sand.

Exercise 15.1 Sand and water

Figure 15.1.5

If you've ever been to the beach, you'll already know that sand behaves differently when it's dry than it does when it's wet, but it's worth taking a systematic look at the differences in its behaviour. Find about half a cup of clean, dry sand (or get some wet sand and dry it out), and then pour it from your hand onto a piece of paper. You should be able to make a cone-shaped pile that has a slope of around 30°. If you pour more sand on the pile, it will get bigger, but the slope should remain the same. Now add some water to the sand so that it is moist. An easy way to do this is to make it completely wet and then let the water drain away for a minute. You should be able to form this moist sand into a steep pile (with slopes of around 80°). Finally, put the same sand into a cup and fill the cup with water so the sand is just covered. Swirl it around so that the sand remains in suspension, and then quickly tip it out onto a flat surface (best to do this outside). It should spread out over a wide area, forming a pile with a slope of only a few degrees.

Water will also reduce the strength of solid rock, especially if it has fractures, bedding planes, or clay-bearing zones. This effect is even more significant when the water is under pressure, which is why you'll often see holes drilled into rocks on road cuts to relieve this pressure. One of the hypotheses advanced to explain the 1965 Hope Slide is that the very cold conditions that winter caused small springs in the lower part of the slope to freeze over, preventing water from flowing out. It is possible that water pressure gradually built up within the slope, weakening the rock mass to the extent that the shear strength was no longer greater than the shear force.

Water also has a particular effect on clay-bearing materials. All clay minerals will absorb a little bit of water, and this reduces their strength. The **smectite** clays (such as the **bentonite** used in cat litter) can absorb a lot of water, and that water pushes the sheets apart at a molecular level and makes the mineral swell. Smectite that has expanded in this way has almost no strength; it is extremely slippery.

And finally, water can significantly increase the mass of the material on a slope, which increases the gravitational force pushing it down. A body of sediment that has 25% porosity and is saturated with water weighs approximately 13% more than it does when it is completely dry, so the gravitational shear force is also 13% higher. In the situation shown in Figure 15.1.1b, a 13% increase in the shear force could easily be enough to tip the balance between shear force and shear strength.

Mass-Wasting Triggers

In the previous section, we talked about the shear force and the shear strength of materials on slopes, and about factors that can reduce the shear strength. Shear force is primarily related to slope angle, and this does not change quickly. But shear strength can change quickly for a variety of reasons, and events that lead to a rapid reduction in shear strength are considered to be **triggers** for mass wasting.

An increase in water content is the most common mass-wasting trigger. This can result from rapid melting of snow or ice, heavy rain, or some type of event that changes the pattern of water flow on the surface. Rapid melting can be caused by a dramatic increase in temperature (e.g., in spring or early summer) or by a volcanic eruption. Heavy rains are typically related to major storms. Changes in water flow patterns can be caused by earthquakes, previous slope failures that dam up streams, or human structures that interfere with runoff (e.g., buildings, roads, or parking lots). An example of this is the deadly 2005 debris flow in North Vancouver (Figure 15.1.6). The 2005 failure took place in an area that had failed previously, and a report written in 1980 recommended that the municipal authorities and residents take steps to address surface and slope drainage issues. Little was done to improve the situation.

Figure 15.1.6 The debris flow in the Riverside Drive area of North Vancouver in January, 2005 happened during a rainy period, but was likely triggered by excess runoff related to the roads at the top of this slope and by landscape features, including a pool, in the area surrounding the house visible here.

In some cases, a *decrease* in water content can lead to failure. This is most common with clean sand deposits (e.g., the upper layer in Figure 15.1.3 (left)), which lose strength when there is no water to hold the grains together.

Freezing and thawing can also trigger some forms of mass wasting. More specifically, the thawing can release a block of rock that was attached to a slope by a film of ice.

One other process that can weaken a body of rock or sediment is shaking. The most obvious source of shaking is an earthquake, but shaking from highway traffic, construction, or mining will also do the job. Several deadly mass-wasting events (including snow avalanches) were triggered by the M7.8 earthquake in Nepal in April 2015.

Saturation with water and then seismic shaking led to the occurrence of thousands of slope failures in the Sapporo area of Hokkaido, Japan in September 2018, as shown on Figure 15.1.7. The area was drenched with rain from tropical storm Jebi on September 4th. On September 6th it was shaken by a M6.6 earthquake which triggered debris flows in the water-saturated volcanic materials on steep slopes. There were 41 deaths related to the slope failures.

Figure 15.1.7 Slope failures in the Sapporo area of Japan following a typhoon (Sept. 4th, 2018) and earthquake (Sept. 6th, 2018) (Before and after Landsat 8 images: left: July 2017, right: September 2018).

Media Attributions

- Figure 15.1.1, 15.1.2, 15.1.3, 15.1.4, 15.1.5: © Steven Earle. CC BY.
- Figure 15.1.6: © *The Province*. Used with permission.
- Figure 15.1.7: "Landslides in Hokkaido" by Lauren Dauphin, NASA Earth Observatory. Public domain.

15.2 Classification of Mass Wasting

It's important to classify slope failures so that we can understand what causes them and learn how to mitigate their effects. The three criteria used to describe slope failures are:

- The type of material that failed (typically either bedrock or unconsolidated sediment)
- The mechanism of the failure (how the material moved)
- The rate at which it moved

The type of motion is the most important characteristic of a slope failure, and there are three different types of motion:

- If the material drops through the air, vertically or nearly vertically, it's known as a **fall**.
- If the material moves as a mass along a sloping surface (without internal motion within the mass), it's a **slide.**
- If the material has internal motion, like a fluid, it's a **flow**.

Unfortunately it's not normally that simple. Many slope failures involve two of these types of motion, some involve all three, and in many cases, it's not easy to tell how the material moved. The types of slope failure that we'll cover here are summarized in Table 15.1.

Table 15.1 Classification of slope failures based on type of material and type of motion

[Skip Table]

Failure Type	Type of Material	Type of Motion	Rate of Motion
Rock fall	Rock fragments	Vertical or near-vertical fall (plus bouncing in many cases)	Very fast (Greater than 10s of metres per second)
Rock slide	A large rock body	Motion as a unit along a planar surface (translational sliding)	Typically very slow (millimetres per year to centimetres per year), but some can be faster
Rock avalanche	A large rock body that slides and then breaks into small fragments	Flow (at high speeds the mass of rock fragments is suspended on a cushion of air)	Very fast (Greater than tens of metres per second)
Creep or solifluction	Soil or other overburden; in some cases, mixed with ice	Flow (although sliding motion may also occur)	Very slow (millimetres per year to centimetres per year)
Slump	Thick deposits (a metre to 10s of metres) of unconsolidated sediment	Motion as a unit along a curved surface (rotational sliding)	Slow (centimetres per year to metres per year)
Mudflow	Loose sediment with a significant component of silt and clay	Flow (a mixture of sediment and water moves down a channel)	Moderate to fast (centimetres per second to metres per second)
Debris flow	Sand, gravel, and larger fragments	Flow (similar to a mudflow, but typically faster)	Fast (metres per second)

Rock Fall

Rock fragments can break off relatively easily from steep bedrock slopes, most commonly due to frost-wedging in areas where there are many freeze-thaw cycles per year. If you've ever hiked along a steep mountain trail on a cool morning, you might have heard the occasional fall of rock fragments onto a **talus slope**. This happens because the water between cracks freezes and expands overnight, and then when that same water thaws in the morning sun, the fragments that had been pushed beyond their limit by the ice fall to the slope below (Figure 15.2.1).

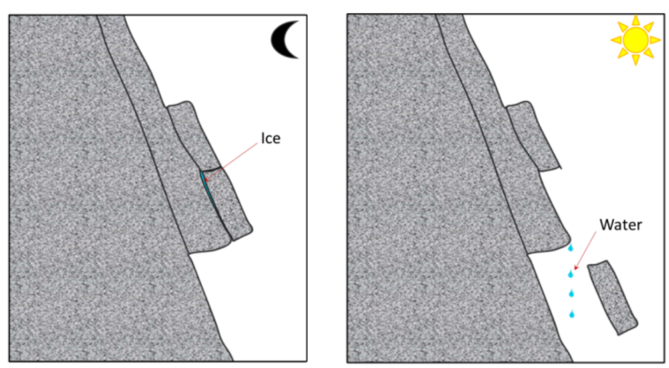

Figure 15.2.1 The contribution of freeze-thaw to rock fall.

A typical talus slope, near Keremeos in southern B.C., is shown in Figure 15.2.2. In December 2014, a large block of rock split away from a cliff in this same area. It broke into smaller pieces that tumbled down the slope and crashed into the road, smashing the concrete barriers and gouging out large parts of the pavement. Luckily no one was hurt.

Figure 15.2.2 Left: A talus slope near Keremeos, B.C., formed by rock fall from the cliffs above. Right: The results of a rock fall onto a highway west of Keremeos in December 2014.

Rock Slide

A rock slide is the sliding motion of rock along a sloping surface. In most cases, the movement is parallel to a fracture, bedding, or metamorphic foliation plane, and it can range from very slow to moderately fast. The word **sackung** describes the very slow motion of a block of rock (millimetres per year to centimetres per year) on a slope. A good example is the Downie Slide north of Revelstoke, B.C., which is shown in Figure 15.2.3. In this case, a massive body of rock is very slowly sliding down a steep slope along a plane of weakness that is approximately parallel to the slope. The Downie Slide, which was first recognized in the 1950s, prior to the construction of the Revelstoke Dam in the late 1970s, was moving very slowly at the time (a few centimetres per year). Geological engineers were concerned that the presence of water in the reservoir (visible in Figure 15.2.3) could further weaken the plane of failure, leading to an acceleration of the motion. The result would have been a catastrophic failure into the reservoir that would have sent a wall of water over the dam and into the community of Revelstoke. During the construction of the dam they tunneled into the rock at the base of the slide and drilled hundreds of drainage holes upward into the plane of failure. This allowed water to drain out so that the pressure was reduced, which reduced the rate of movement of the sliding block. BC Hydro monitors this site continuously; the slide block is currently moving more slowly than it was prior to the construction of the dam.

Figure 15.2.3 The Downie Slide, a sackung, on the shore of the Revelstoke Reservoir (above the Revelstoke Dam). The head scarp is visible at the top and a side-scarp along the left side.

In the summer of 2008, a large block of rock slid rapidly from a steep slope above Highway 99 near Porteau Cove (between Horseshoe Bay and Squamish). The block slammed into the highway and adjacent railway and broke into many pieces. The highway was closed for several days, and the slope was subsequently stabilized with rock bolts and drainage holes. As shown in Figure 15.2.4, the rock is fractured parallel to the slope, and this almost certainly contributed to the failure. However, it is not actually known what triggered this event as the weather was dry and warm during the preceding weeks, and there was no significant earthquake in the region.

Figure 15.2.4 Site of the 2008 rock slide at Porteau Cove. Notice the prominent fracture set parallel to the surface of the slope. The slope has been stabilized with rock bolts (visible near to the top of the photo) and holes have been drilled into the rock to improve drainage (one is visible in the lower right). Risk to passing vehicles from rock fall has been reduced by hanging mesh curtains (background).

Rock Avalanche

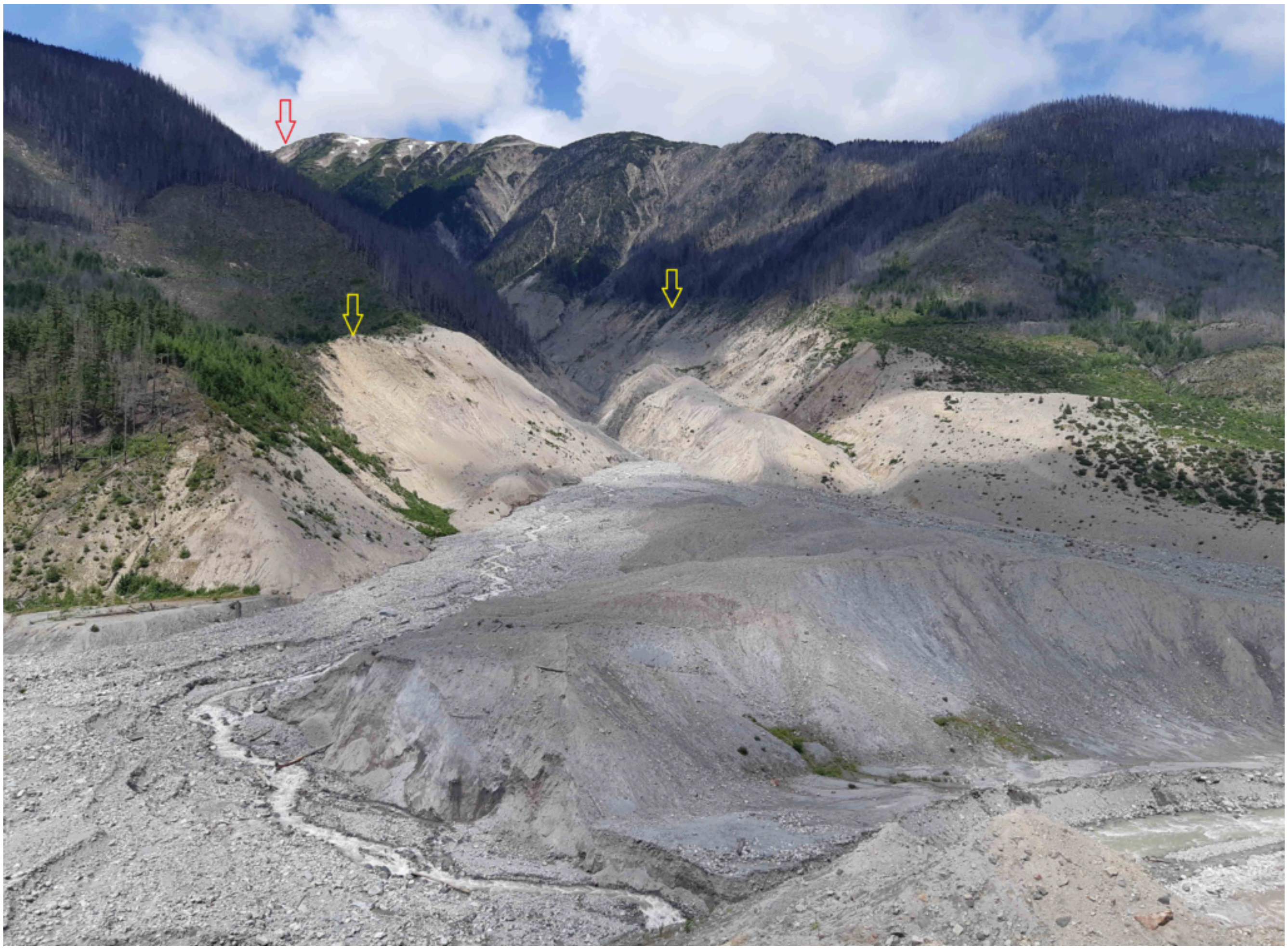

Figure 15.2.5 The August 2010 Mount Meager rock avalanche, showing where the slide originated (red arrow, 4 km upstream) and its path down a steep narrow valley. The yellow arrows show how far up the valley the avalanche extended.

If a rock slides and then starts moving quickly (metres per second), the rock is likely to break into many small pieces, and at that point it turns into a **rock avalanche**, in which the large and small fragments of rock move in a fluid manner supported by a cushion of air within and beneath the moving mass. The 1965 Hope Slide (Figure 15.0.1) was a rock avalanche, as was the famous 1903 Frank Slide in southwestern Alberta. The 2010 slide at Mount Meager (west of Lillooet) was also a rock avalanche, and rivals the Hope Slide as the largest slope failure in Canada during historical times (Figure 15.2.5).

Creep or Solifluction

The very slow—millimetres per year to centimetres per year—movement of soil or other unconsolidated material on a slope is known as creep. **Creep**, which normally only affects the upper several centimetres of loose material, is typically a type of very slow flow, but in some cases, sliding may take place. Creep can be facilitated by freezing and thawing because, as shown in Figure 15.2.6, particles are lifted perpendicular to the surface by the growth of ice crystals within the soil, and then let down vertically by gravity when the ice melts. The same effect can be produced by frequent wetting and drying of the soil. In cold environments, **solifluction** is a more intense form of freeze-thaw-triggered creep.

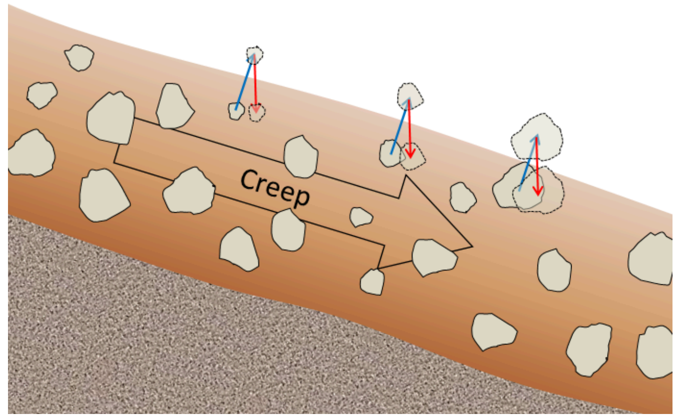

Figure 15.2.6 A depiction of the contribution of freeze-thaw to creep. The blue arrows represent uplift caused by freezing in the wet soil underneath, while the red arrows represent depression by gravity during thawing. The uplift is perpendicular to the slope, while the drop is vertical.

Creep is most noticeable on moderate-to-steep slopes where trees, fence posts, or grave markers are consistently leaning in a downhill direction. In the case of trees, they try to correct their lean by growing upright, and this leads to a curved lower trunk known as a "pistol butt." An example is shown on Figure 15.2.7.

Figure 15.2.7 Pistol-butt shaped trees on a slope that is experiencing creep

Slump

Slump is a type of slide (movement as a mass) that takes place within thick unconsolidated deposits (typically thicker than 10 metres). Slumps involve movement along one or more curved failure surfaces, with downward motion near the top and outward motion toward the bottom (Figure 15.2.8). They are typically caused by an excess of water within these materials on a steep slope.

An example of a slump in the Lethbridge area of Alberta is shown in Figure 15.2.9. This feature has likely been active for many decades, and moves a little more whenever there are heavy spring rains and significant snowmelt runoff. The toe of the slump is failing because it has been eroded by the small stream at the bottom.

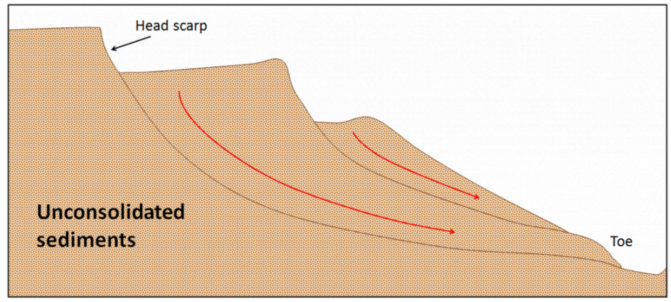

Figure 15.2.8 A depiction of the motion of unconsolidated sediments in an area of slumping.

Figure 15.2.9 A slump along the banks of a small coulee near Lethbridge, Alberta. The main head-scarp is clearly visible at the top, and a second smaller one is visible about one-quarter of the way down. The toe of the slump is being eroded by the seasonal stream that created the coulee.

Mudflows and Debris Flows

As you saw in Exercise 15.1, when a mass of sediment becomes completely saturated with water, the mass loses strength, to the extent that the grains are pushed apart, and it will flow, even on a gentle slope. This can happen during rapid spring snowmelt or heavy rains, and is also relatively common during volcanic eruptions because of the rapid melting of snow and ice. (A mudflow or debris flow on a volcano or during a volcanic eruption is a *lahar*.) If the material involved is primarily sand-sized or smaller, it is known as a mudflow, such as the one shown in Figure 15.2.10.

Figure 15.2.10 A slump (left) and an associated mudflow (centre) at the same location as Figure 15.2.9, near Lethbridge, Alberta.

If the material involved is gravel sized or larger, it is known as a debris flow. Because it takes more gravitational energy to move larger particles, a debris flow typically forms in an area with steeper slopes and more water than does a mudflow. In many cases, a debris flow takes place within a steep stream channel, and is triggered by the collapse of bank material into the stream. This creates a temporary dam, and then a major flow of water and debris when the dam breaks. This is the situation that led to the fatal debris flow at Johnsons Landing, B.C., in 2012. A typical west-coast debris flow is shown in Figure 15.2.11. This event took place in November 2006 in response to very heavy rainfall. There was enough energy to move large boulders and to knock over large trees.

Figure 15.2.11 The lower part of debris flow within a steep stream channel near Buttle Lake, B.C., in November 2006.

Exercise 15.2 Classifying slope failures

These four photos show some of the different types of slope failures described above. Try to identify each types and provide some criteria to support your choice.

Figure 15.2.12a

Figure 15.2.12b

Figure 15.2.12c

Figure 15.2.12d

a:	b:
c:	d:

See Appendix 3 for Exercise 15.2 answers.

Media Attributions

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15.3 Preventing, Delaying, Monitoring, and Mitigating Mass Wasting

As already noted, we cannot prevent mass wasting in the long term as it is a natural and ongoing process; however, in many situations there are actions that we can take to reduce or mitigate its damaging effects on people and infrastructure. Where we can neither delay nor mitigate mass wasting, we should consider moving out of the way.

Preventing and Delaying Mass Wasting

It is comforting to think that we can prevent some effects of mass wasting by mechanical means, such as the rock bolts in the road cut at Porteau Cove (Figure 15.2.4), or the drill holes used to drain water out of a slope, as was done at the Downie Slide (Figure 15.2.3), or the building of physical barriers, such as retaining walls. What we have to remember is that the works of humans are mostly insignificant compared to the works of nature. The rock bolts in the road cut at Porteau Cove will slowly start to corrode after a few years, and within a few decades, many of them will begin to lose their strength. Unless they are replaced, they will no longer support that slope. Likewise, drainage holes at the Downie Slide will eventually become plugged with sediment and chemical precipitates, and unless they are periodically unplugged, their effectiveness will decrease. Eventually, unless new holes are drilled, the drainage will be so compromised that the slide will start to move again. This is why careful long-term slope monitoring by geological and geotechnical engineers is important at these sites. The point here is that our efforts to “prevent” mass wasting are only as good as our resolve to maintain those preventive measures.

Delaying mass wasting is a worthy endeavour, of course, because during the time that the measures are still effective they can save lives and reduce damage to property and infrastructure. The other side of the coin is that we must be careful to avoid activities that could make mass wasting more likely. One of the most common anthropogenic causes of mass wasting is road construction, and this applies both to remote gravel roads built for forestry and mining and large urban and regional highways. Road construction is a potential problem for two reasons. First, creating a flat road surface on a slope inevitably involves creating a cut bank that is steeper than the original slope. This might also involve creating a filled bank that is both steeper and weaker than the original slope (Figure 15.2.12). Second, roadways typically cut across natural drainage features, and unless great care is taken to reroute the runoff water and prevent it from forming concentrated flows, oversaturating fill of materials can result. A specific example of the contribution of construction-related impeded drainage to slope instability was shown earlier in Figure 15.1.6.

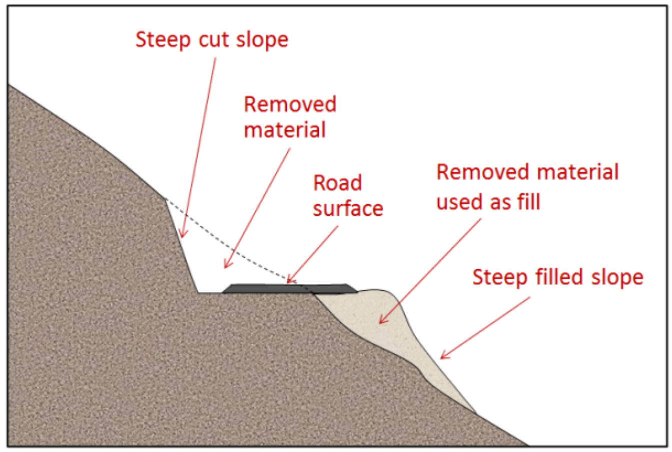


Figure 15.3.1 An example of a road constructed by cutting into a steep slope. The cut material was moved to outside part of the road to act as fill.

Apart from water issues, engineers building roads and other infrastructure on bedrock slopes have to be acutely aware of the geology, and especially of any weaknesses or discontinuities in the rock related to bedding, fracturing, or foliation. If possible, situations like that at Porteau Cove (Figure 15.2.3) should be avoided — by building somewhere else — rather than trying to stitch the slope back together with rock bolts.

It is widely believed that construction of buildings on the tops of steep slopes can contribute to the instability of the slope. This is probably true, but in most cases that is not because of the weight of the building. As you'll see by completing Exercise 15.3, a typical house isn't usually heavier than the fill that was removed from the hole in the ground made to build it. A more likely contributor to instability of the slope around a building is the effect that it and the changes made to the surrounding area have on drainage.

Exercise 15.3 How much does a house weigh, and can it contribute to a slope failure?

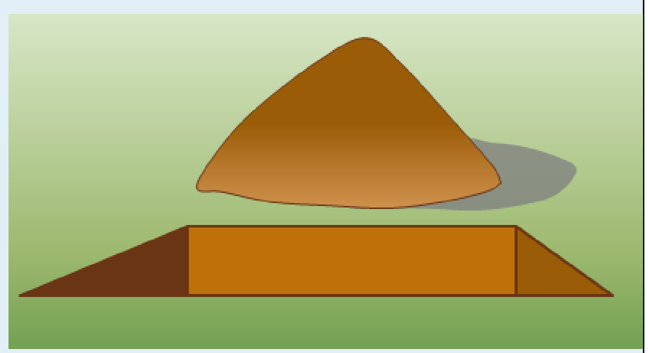


Figure 15.3.2

It is commonly believed that building a house (or some other building) at the top of a slope will add a lot of extra weight to the slope, which could contribute to slope failure. But what does a house actually weigh? A typical 150 square metre (approximately 1,600 square feet) wood-frame house with a basement and a concrete foundation weighs about 145 tonnes. But most houses are built on foundations that are excavated into the ground. This involves digging a hole and taking some material away, so we need to subtract what that excavated material weighs. Assuming our 150 square metre house required an excavation that was 15 metres by 11 metres by 1 metre deep, that's 165 cubic metres of "dirt," which typically has a density of about 1.6 tonnes per cubic metre.

Calculate the weight of the soil that was removed and compare that with the weight of the house and its foundation.

If you're thinking that building a bigger building is going to add more weight, consider that bigger buildings need bigger and deeper excavations, and in many cases the excavations will be into solid rock, which is much heavier than surficial materials.

Much more important than worrying about the weight of a building is to consider how a building might change the drainage on a slope. There are a number ways. Water can be collected by roofs, go into downspouts, and form concentrated flows that are directed onto or into the slope. Likewise drainage from nearby access roads, lawn irrigation, leaking pools, and septic systems can all alter the surface and groundwater flow in a slope.

See Appendix 3 for [Exercise 15.3 answers].

Monitoring Mass Wasting

In some areas, it is necessary to establish warning systems so that we know if conditions have changed at a known slide area, or if a rapid failure, such as a debris flow, is actually on its way downslope. The Downie Slide above the Revelstoke Resevoir is monitored 24/7 with a range of devices, such as inclinometers (slope-change detectors), bore-hole motion sensors, and GPS survey instruments. A simple mechanical device for monitoring the nearby Checkerboard Slide (which is also above the Revelstoke Reservoir) is shown in Figure 15.3.3. Both of these are very slow-moving rock slides, but it's critically important to be able to detect changes in their rates of motion because at both of these locations a rapid failure would result in large bodies of rock plunging into the reservoir and sending a wall of water over the Revelstoke Dam, potentially destroying the nearby town of Revelstoke.

Figure 15.3.3 Part of a motion-monitoring device at the Checkerboard Slide near Revelstoke, B.C. The lower end of the cable is attached to a block of rock that is unstable. Any incremental motion of that block will move the cable, which will be detectable on this device.

Mount Rainier, a glacier-covered volcano in Washington State, has the potential to produce massive mudflows or debris flows (lahars) with or without a volcanic eruption. Over 100,000 people in the Tacoma, Puyallup, and Sumner areas are in harm's way because many of them currently reside on deposits from past lahars (Figure 15.3.3). In 1998, a network of acoustic monitors was established around Mount Rainier. The monitors are embedded in the ground adjacent to expected lahar paths. They are intended to provide warnings to emergency officials, and when a lahar is detected, the residents of the area will have anywhere from 40 minutes to three hours to get to safe ground.

Figure 15.3.4 Mount Rainier, Washington, from Tacoma.

Mitigating the Impacts of Mass Wasting

In situations where we can't predict, prevent, or delay mass-wasting, some effective measures can be taken to minimize the associated risk. For example, many highways in B.C. and western Alberta have avalanche shelters like that shown in Figure 15.3.5. In some parts of the world, similar features have been built to protect infrastructure from other types of mass wasting.

Figure 15.3.5 A snow avalanche shelter on the Coquihalla Highway. The expected path of the avalanche is the steep un-treed slope above.

Debris flows are inevitable, unpreventable, and unpredictable in many parts of B.C., but nowhere more so than along the Sea-to-Sky Highway between Horseshoe Bay and Squamish. The results have been deadly and expensive many times in the past. It would be very expensive to develop a new route in this region, so provincial authorities have taken steps to protect residents and traffic on the highway and the railway. Debris-flow defensive structures have been constructed in several drainage basins, as shown in Figure 15.3.6. One strategy is to allow the debris to flow quickly through to the ocean along a smooth channel. Another is to capture the debris within a constructed basin that allows the excess water to continue through, but catches the debris materials.

Figure 15.3.6 Two strategies for mitigating debris flows on the Sea-to-Sky Highway. Left: A concrete –lined channel on Alberta Creek allows debris to flow quickly through to the ocean. Right: A debris-flow catchment basin on Charles Creek. In 2010, a debris flow filled the basin to the level of the dotted white line.

Finally, in situations where we can't do anything to delay, predict, contain, or mitigate slope failures, we simply have to have the sense to stay away. There is a famous example of this in B.C. at a site known as Garibaldi, 25 kilometres south of Whistler. In the early 1980s the village of Garibaldi had a population of about 100, with construction underway on some new homes, and plans for many more. In the months that followed the deadly 1980 eruption of Mount St. Helens in Washington State, the B.C. Ministry of Transportation commissioned a geological study that revealed that a steep cliff known as The Barrier (Figure 15.3.7) had collapsed in 1855, leading to a large rock avalanche, and that it was likely to collapse again unpredictably, putting the village of Garibaldi at extreme risk. In an ensuing court case, it was ruled that the Garibaldi site was not a safe place for people to live. Those who already had homes there were compensated, and everyone else was ordered to leave.

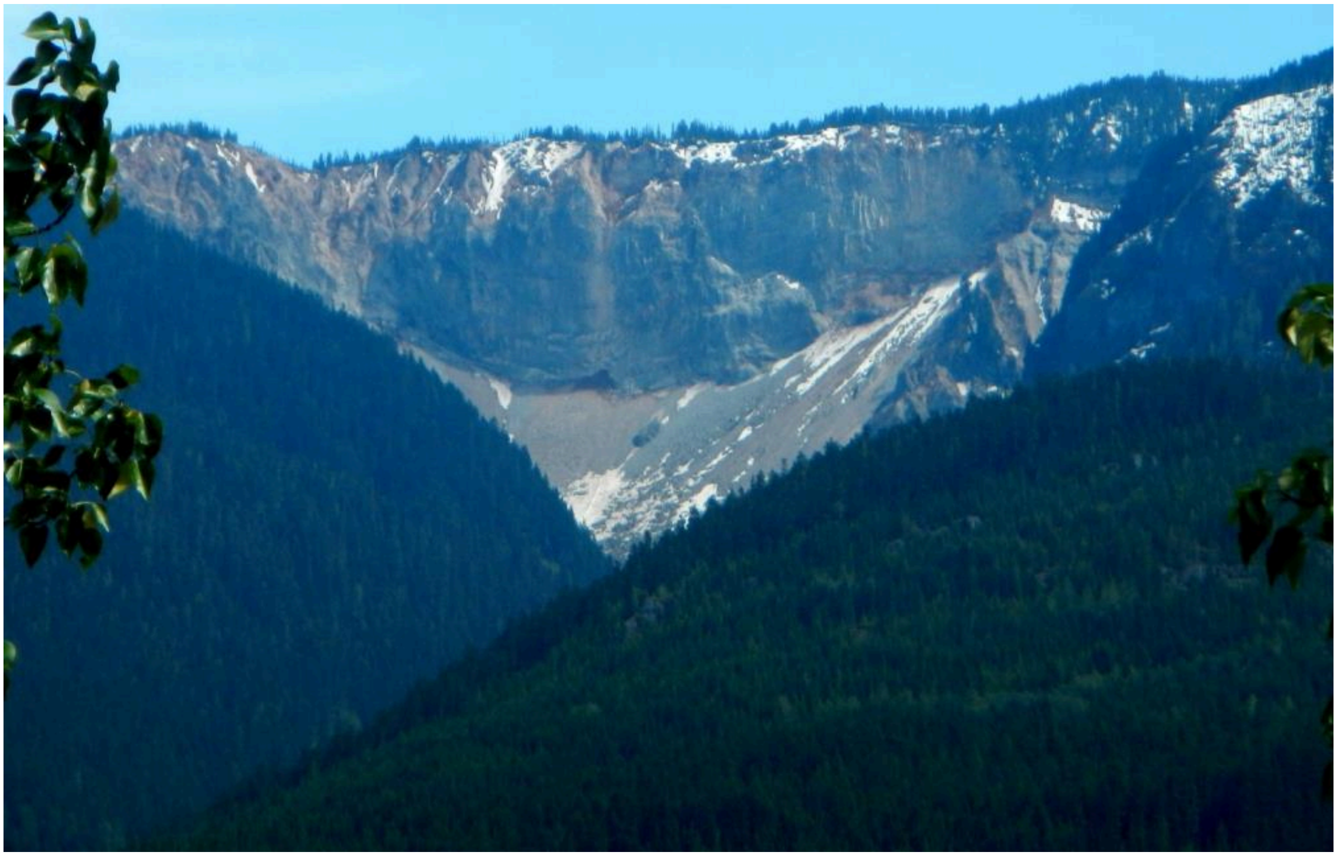


Figure 15.3.7 The Barrier, south of Whistler, B.C., was the site of a huge rock avalanche in 1855, which extended from the cliff visible here 4 kilometres down the valley and across the current location of the Sea-to-Sky Highway and the Cheakamus River.

Media Attributions

- Figure 15.3.1, 15.3.2, 15.3.3, 15.3.5, 15.3.6, 15.3.7: © Steven Earle. CC BY.
- Figure 15.3.4: "Mount Rainier over Tacoma" by Lyn Topinka (USGS). Public domain.

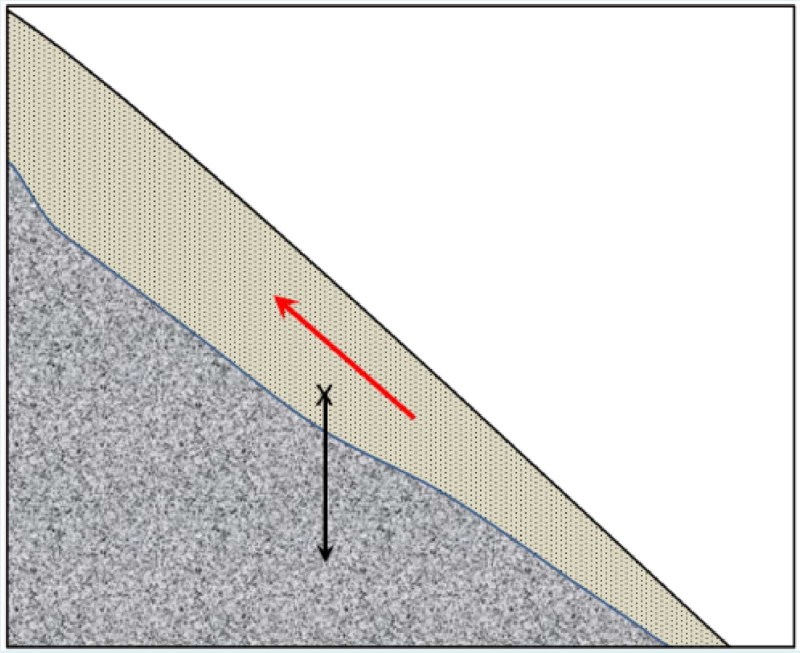
Summary

The topics covered in this chapter can be summarized as follows:

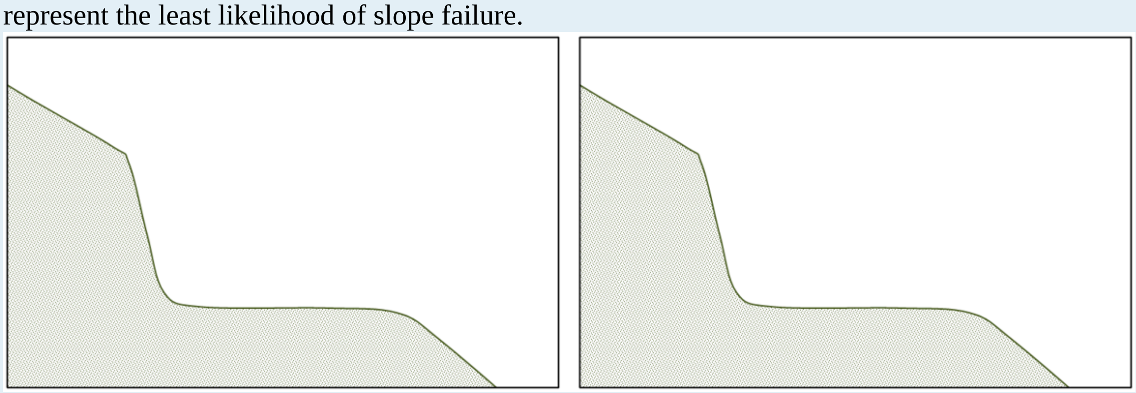
Section	**Summary**
15.1 Factors That Control Slope Stability	Slope stability is controlled by the slope angle and the strength of the materials on the slope. Slopes are a product of tectonic uplift, and their strength is determined by the type of material on the slope and its water content. Rock strength varies widely and is determined by internal planes of weakness and their orientation with respect to the slope. In general, the more water, the greater the likelihood of failure. This is especially true for unconsolidated sediments, where excess water pushes the grains apart. Addition of water is the most common trigger of mass wasting, and can come from storms, rapid melting, or flooding.
15.2 Classification of Mass Wasting	The key criterion for classifying mass wasting is the nature of the movement that takes place. This may be a precipitous fall through the air, sliding as a solid mass along either a plane or a curved surface, or internal flow as a viscous fluid. The type of material that moves is also important—specifically whether it is solid rock or unconsolidated sediments. The important types of mass wasting are creep, slump, translational slide, rotational slide, fall, and debris flow or mudflow.
15.3 Preventing, Delaying, Monitoring, and Mitigating Mass Wasting	We cannot prevent mass wasting, but we can delay it through efforts to strengthen the materials on slopes. Strategies include adding mechanical devices such as rock bolts or ensuring that water can drain away. Such measures are never permanent, but may be effective for decades or even centuries. We can also avoid practices that make matters worse, such as cutting into steep slopes or impeding proper drainage. In some situations, the best approach is to mitigate the risks associated with mass wasting by constructing shelters or diversionary channels. And in other cases, where slope failure is inevitable, we should simply avoid building anything there.

Questions for Review

Answers to Review Questions can be found in Appendix 2.



1. In the scenario shown here, the gravitational force on the unconsolidated sediment overlying the point marked with an X is depicted by the black arrow. Draw in the two arrows that show how this force can be resolved into the shear force (along the slope) and the normal force (into the slope).
2. The red arrow in the diagram depicts the shear strength of the sediment. Assuming that the relative lengths of the shear force arrow (which you drew in question 1), and the shear strength arrow are indicative of the likelihood of failure, predict whether this material is likely to fail or not.
3. After several days of steady rain, the sediment becomes saturated with water and its strength is reduced by 25%. What are the likely implications for the stability of this slope?
4. The diagrams below represent a cross-section of a road cut that has been constructed in sedimentary rock. In the first diagram, draw in the orientation of the bedding that would represent the greatest likelihood of slope failure. In the second diagram, show the orientation that would represent the least likelihood of slope failure.



5. Explain why moist sand is typically stronger than either dry sand or saturated sand.
6. In the context of mass wasting, how does a flow differ from a slide?

7. If a large rock slide starts moving at a rate of several metres per second, what is likely to happen to the rock, and what would the resulting failure be called?
8. In what ways does a debris flow differ from a typical mudflow?
9. In the situation described in the chapter regarding lahar warnings at Mount Rainier, the residents of the affected regions have to assume some responsibility and take precautions for their own safety. What sort of preparation should the residents make to ensure that they can respond appropriately when they hear lahar warnings?
10. What factors are likely to be important when considering the construction of a house near the crest of a slope that is underlain by glacial sediments?