MASS WASTING

Mass Wasting, is the failure and downslope movement of rock or unconsolidated materials in response to gravity. A landslide is a type of mass wasting event. An important reason for learning about mass wasting is to minimize risks from these events. Geologists, engineers, and others study the nature of the materials that fail, and how and why they fail. Using this knowledge, they classify mass-wasting events. In this chapter, we will learn more about the science behind mass wasting.

Mass wasting in Arizona is common; far more common than people think. The steepness of Arizona's mountains, plateaus, mesas, and buttes, coupled with intense rain through monsoon events, provides the perfect landscape for mass wasting to occur. In the U.S., mass wasting events are a costly natural hazard, causing dozens of fatalities and ~$2 – 4 billions of damage to infrastructure, roads, buildings and homes annually (2). Below you can see some images of recent mass wasting events in Arizona.

Video 7.1 Select landslides in Arizona – translational, rotational, toreva blocks, slumps and debris flows. (00:56)

Arizona State Geological Survey, CC-BY

Learning Objectives
Explain how slope stability relates to slope angle.
Summarize 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.
List and describe 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 measures that can be taken to mitigate the risks associated with mass wasting.
Describe the mass wasting potential in Arizona.

7.1 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. (1)

Figure 7.1.1 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. Steven Earle CC-BY.

Figure 7.1.1 shows a block of rock on a rock slope. The block is being pulled toward Earth's center (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 (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 7.1.1a, it is greater than the shear force, so the block should not move. In Figure 7.1.1b 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 7.1.1c, the slope is steeper still, so the shear force is considerably greater than the shear strength, and the block will very likely move. (1)

Variability Due to Rock Type

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. Some limestones are strong, most sandstone and conglomerate are moderately strong, and some sandstone and all shale are quite weak. 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.

Fractures, metamorphic foliation, or bedding can significantly reduce the strength of a body of rock, and in 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. We illustrate this in Figure 7.1.2. 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. (1)

Figure 7.1.2. Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations.

Affects of Water

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, but it also applies to bodies of rock. 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. (1)

Figure 7.1.3. Depiction of dry, moist, and saturated sand.

Digging Deeper: Sand, Water, and the Angle of Repose

An image of a pile of sand at the maximum angle that it can maintain

Figure 7.1.5. The angle of repose for sand. Wikicommons, CC-BY-SA.

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 behavior. 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. This is called the angle of repose, or the steepest angle formed by a certain loose material. 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°). The angle of repose increases, because the sediments are more cohesive in water. 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. The angle of repose is less with additional water.

Water will also reduce the strength of solid rock, especially if it has fractures, bedding planes, or clay-bearing zones. All clay minerals will absorb a bit of water, and this reduces their strength. The clays can absorb a lot of water, and that water pushes the sheets apart at a molecular level and makes the mineral swell. Water can also significantly increase the mass of the material on a slope. In Figure 7.1.1b, an increase in the shear force could easily be enough to tip the balance between shear force and shear strength. (1)

Triggers of Mass Wasting

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). In some cases, a decrease in water content can lead to failure. This is most common with clean sand deposits, 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. (1)

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.

Of course, a combination of triggers can have devastating effects. 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 in Figure 7.1.5. 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 7.1.5. 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). “Landslides in Hokkaido” by Lauren Dauphin, NASA Earth Observatory. Public domain.

An over steepened slope may also trigger landslides. Slopes can be made excessively steep by natural processes of erosion or when humans modify the landscape for building construction. An example of how a slope may be oversteepened during development occurs where the bottom of the slope is cut into, perhaps to build a road or level a building lot, and the top of the slope is modified by depositing excavated material from below. If done carefully, this practice can be very useful in land development, but in some cases, this can result in devastating consequences. (3)

Backyard Geology: Black Canyon Landslide

image

Figure 7.1.6. Black Canyon Landslide, annotated. Photo by B. Gootee, annotation J. Cook, AZGS. CC-BY.

Arizona has over 8,000 documented landslide features, but they have occurred due to a variety of reasons. Figure 7.1.6 shows a small (less than 0.1 square miles) landslide that occurred near Black Canyon City, Arizona. This feature shows tension cracks. The portion labeled “head scarp” is the part of the butte that has stayed in place and is now exposed from the mass wasting event. The entire area is a series of flat-topped mesas comprised of lava flows and overlying shale, mudstone, and clays. The slide at Black Canyon City has shown recent movement and is still observed and studied!

7.2 Classification of Mass Wasting

We 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:

Material: Type of material that failed (typically either bedrock or unconsolidated sediment)
Motion: How the material moved (fall, slide, or flow).
Rate: Speed at which the material moved.
Three types of motion associated with slope failure are:

Fall: Material drops through the air, vertically or nearly vertically.
Slide: Material moves as a cohesive mass along a sloping surface.
Flow: Material moves like a fluid.
Unfortunately, it’s not normally that simple. Many slope failures involve two of these types of motion, some involve all three, and most times, it’s not easy to tell how the material moved. The types of slope failure that we’ll cover here are summarized in Table 7.1, though there are other types of mass wasting.

Table 7.1 Classification of slope failures based on type of material and type of motion. Extremely rapid = more than 3m/sec, Rapid = 0.3m/min, Moderate = 1.5 m/day, Very slow = 1.5m/year Extremely slow = 0.3 m/5years
[Skip Table]

Failure Type	Type of Material	Type of Motion	Rate of Motion
Rock fall	Bedrock	Fall	Extremely rapid
Rock slide	Bedrock	Slide	Very slow to extremely rapid
Rock avalanche	Bedrock (slides then breaks into smaller fragments)	Flow	Extremely rapid
Creep or solifluction	Unconsolidated materials (rock fragments, soils)	Flow or slide	Extremely slow
Slump	Unconsolidated sediments	Slide	Very slow to moderate
Mudflow	Unconsolidated sediments (very small silt and clay)	Flow	Moderate to Extremely rapid
Debris flow	Unconsolidated sediments (Sand, gravel, and larger fragments)	Flow	Rapid to Extremely rapid

Rock Fall

Figure 7.2.1. The contribution of freeze-thaw to 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. When water freezes to form ice, its volume increases by about 8%, this causes fractures to enlarge. When the ice melts, more water can fill the larger crack, and refreeze. This process, over time, can cause large pieces of solid rock to fall (Fig 7.2.1). However, it can occur due to other triggers, particularly heavy rain, which adds weight or loosens material.

A rock fall in Verde Valley, Arizona, caused tons of solid material to fall to the valley below, destroying an RV but stopping short of hitting the house (Figure 7.2.2). Luckily, no one was hurt in this rock fall, but living at the base of a cliff can be very dangerous and a fall is likely to happen again.

image

Figure 7.2.2. Boulder smashes an RV in Verde Valley, AZ. AZGS, CC-BY

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.

On June 23, 1925, a 38 million cubic meter rock slide occurred next to the Gros Ventre River (pronounced “grow vont”) near Jackson Hole, Wyoming. Large boulders dammed the Gros Ventre River and ran up the opposite side of the valley several hundred vertical feet. The dammed river created Slide Lake, and two years later in 1927, lake levels rose high enough to destabilize the dam. The dam failed and caused a catastrophic flood that killed six people in the small downstream community of Kelly, Wyoming.

Shows a before and after scenario of the Gros Ventre slide area with bedding parallel to the surface and oversteepending caused by the river. The "after" image show how the rock material slide along a bedding plane.

Figure 7.2.3. Cross-section of 1925 Gros Ventre slide showing sedimentary layers parallel with the surface and undercutting (oversteepening) of the slope by the river.

A combination of three factors caused the rock slide: 1) heavy rains and rapidly melting snow saturated the sandstone causing the underlying shale to lose its shear strength, 2) the Gros Ventre River cut through the sandstone creating an over-steepened slope, and 3) soil on top of the mountain became saturated with water due to poor drainage. The cross-section diagram shows how the parallel bedding planes between the sandstone and clay/limestone offered little friction against the slope surface as the river undercut the sandstone. Lastly, the rockslide may have been triggered by an earthquake. (3)

Rock Avalanche

Figure 7.2.5. 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. Earle, I. CC-BY.

If a rock slides and then moves quickly (meters 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 2010 slide at Mount Meager (north of Vancouver, British Columbia, Canada) was a rock avalanche, and is the largest slope failure in Canada during historical times (Figure 7.2.5). Though no one was harmed during this event, there is a great potential for damage and loss of life from this type of mass wasting. (1)

Creep or Solifluction

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Figure 7.2.6. 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. S. Earle, CC-BY.

The very slow—millimeters per year to centimeters per year—movement of soil or other unconsolidated material on a slope is known as creep. Creep, which normally only affects the upper several centimeters 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 7.2.6, 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. Creep is most noticeable on moderate-to-steep slopes where trees, fence posts, or grave markers are consistently leaning in a downhill direction. With trees, they try to correct their lean by growing upright, and this leads to a curved lower trunk, shown on Figure 7.2.7.

Figure 7.2.7. Trees on a slope that is experiencing creep, notice the bent lower trunk. S. Earle, CC-BY.

Slump

A depiction of the motion of unconsolidated sediments in an area of slumping

Figure 7.2.8. A depiction of the motion of unconsolidated sediments in an area of slumping. S. Earle, CC-BY.

Slump is a type of slide (movement as a mass) that takes place within thick unconsolidated deposits (typically thicker than 10 meters). Slumps involve movement along one or more curved failure surfaces, with downward motion near the top and outward motion toward the bottom (Figure 7.2.8). 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 7.2.9. 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.

A slump. 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 a seasonal stream.
Figure 7.2.9 A slump. 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 a seasonal stream. S. Earle, CC-BY.

Mudflows and Debris Flows

A slump (left) and an associated mudflow (center).
Figure 7.2.10. A slump (left) and an associated mudflow (center) Earle, CC-BY.

As you saw previously, 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 7.2.10.

A debris flow from SE Arizona
Figure 7.2.11. A debris flow from SE Arizona. Youberg, A. AZGS, CC-BY.

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. Large amounts of debris can be carried.

7.3 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 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.

Predicting

The best way to predict mass wasting is to understand the factors and triggers associated with events. In addition, a new model from NASA provides near real-time threat tracking through satellite data. The model estimates potential landslide activity triggered by rainfall, the most widespread trigger, and provides it for global analysis. This model could potentially improve estimates of long-term patterns and contribute to future prediction of catastrophic landslide events.

Video 7.3.1.

Preventing and Delaying Mass Wasting

image

Figure 7.3.1. Bolts are used to keep rock face in place. Kitt Peak, Arizona. M. Conway, AZGS

It is comforting to think that we can prevent some effects of mass wasting by mechanical means, such as the rock bolts in a road cut (Fig 7.3.1), or the drill holes used to drain water out of a slope, as was done in Figure 7.2.3, 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 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 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. (1)

Delaying mass wasting is a worthy endeavor, 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 7.3.2). 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.

Figure 7.3.2. 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. S. Earle CC-BY

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 these 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. 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.

Backyard Geology: Mitigating a landslide on US-89

In 2013, a landslide destroyed a 23-mile stretch of highway US-89, cutting off a heavily used route to Page, AZ. The repair took almost 2 years and involved literally moving a mountain. Watch the video below from the Arizona Department of Transportation that shows the reopened road!

Video 7.3.2.

Monitoring Mass Wasting

A motion-monitoring device is dug into the ground. It has a cable that is attached to an unstable rock

Figure 7.3.2. Part of a motion-monitoring device. S. Earle, CC-BY.

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. Monitoring may occur 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 is shown in Figure 7.3.2. 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 the device. Though a slope may be slow moving, it's critically important to be able to detect changes in their rates of motion at places with high potential for disaster.

Mount Ranier over Tacoma

Figure 7.3.3. Mount Rainier over Tacoma. L. Topinka, USGS, Public Domain.

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. 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. (1)

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 western Canada have avalanche shelters like that shown in Figure 7.3.5. In some parts of the world, similar features have been built to protect infrastructure from other types of mass wasting.

Figure 7.3.4. A snow avalanche shelter on the Coquihalla Highway, B.C., Canada. The expected path of the avalanche is the steep, un-treed slope above. S. Earle, CC-BY.

Debris flows are inevitable, unpreventable, and unpredictable in many places. Debris-flow defensive structures can be constructed in drainage basins, as debris follows the same paths as streams. Figure 7.3.5 shows two strategies for dealing with debris flows. 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 7.3.5. Two strategies for mitigating debris flows in western Canada. Left: A concrete –lined channel along a creek allows debris to flow quickly through to the ocean. Right: A debris-flow catchment basin along a 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., Canada, at a site known as Garibaldi. 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 (Figure 7.3.6) 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. (1)

This was the site of a huge rock avalanche in 1855, which extended from the cliff visible here 4 kilometers down the valley and into the river.

Figure 7.3.6. This was the site of a huge rock avalanche in 1855, which extended from the cliff visible here 4 kilometers down the valley and into the river. S. Earle, CC-BY

7.4 Subsidence

Subsidence occurs when loose, water-saturated sediment begins to compact, causing the ground surface to collapse. Now there are two types of subsidence.

Slow Subsidence

Slow subsidence occurs when the water within the sediment is slowly squeezed out because of overlying weight. There are several examples of slow subsidence, but the best one is Venice, Italy. Venice was built at sea level on the now submerged delta of the Brenta River. The city is sinking because of the overlying weight of the city and the pumping of groundwater. The problem now is that sea levels are rising as glaciers melt and water expands due to global warming. (3)

image

Fiigure 7.4.1 “Gondola on the Grand Canal, Venice, Italy” by Peter K Burian, CC-BY

An example of slow subsidence in the U.S. includes New Orleans, Louisiana. As we all know from Hurricane Katrina, the Mississippi River has a vast network of levees that prevent the massive river from flooding – most of the time. But by preventing the spring-time flooding, we are preventing the river from depositing sediment onto the land. Instead, the sediment is being transported to the Gulf of Mexico creating the massive Mississippi delta (3).

Fast Subsidence

Fast subsidence occurs when naturally acidic water begins to dissolve limestone rock to form a network of water-filled underground caverns. But if droughts or pumping of groundwater reduces the water table below the level of the caves, they caverns collapse creating surface sinkholes. A dramatic example of fast subsidence occurred in Guatemala City in 2007 when a massive sinkhole formed 300 feet deep. As noted above, the underground region surrounding Guatemala is composed of limestone and a vast underground network of caverns. It is believed that the water table has been dropping in the region and thus draining the caves. Afterward, the caves can not support the overlying weight and collapse in. (3)

Backyard Geology: McCauley Sinks, Holbrook Basin, AZ

Arizona is home to many sinkholes, one notable set is in the northeastern part of the state. McCauley Sinks (Figure 7.4.2) comprises several dozen small sinkholes restricted to a 3-km-wide depression. The sinks are arranged in a series of gentle arcs or rings. The size of individual sinks varies, but the largest are ~ 100 m in diameter and 50 m deep. The sinks crop out in Permian Kaibab Formation limestones. Collapse here may be the result of Karst formations in the older Permian Schnebly Hill Formation, which contains evaporites, principally halite (rock salt). (5)

Image of sinkholes

Figure 7.4.2 McCauley Sinks, Holbrook, Arizona. M. Conway, AZGS, CC-BY

7.5 Attribution and References

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Arizona State Geological Survey (n.d.) Retrieved April 19, 2021 from
https://youtu.be/w8bRRixHe3g

Photographs of recent landslide deposits in Arizona.
7.1
7.1.1 Earle, S. (n.d.) Retrieved April 21, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/06/Differences-in-the-shear-and-normal-components-1024×919.png

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.
7.1.2 Earle, S (n.d.) Retrieved April 21, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Relative-stability-of-slopes-as-a-function-of-the-orientation-of-weaknesses-1024×356.png

Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations.
7.1.3 Earle, S (n.d.) Retrieved April 21, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Depiction-of-dry-moist-and-saturated-sand.png

Depiction of dry, moist, and saturated sand.
7.1.4 Earle, S (n.d.) Retrieved April 21, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Sand-and-Water-1024×768.jpg

Photograph of sand castles
7.1.5   Retrieved April 21, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/hokkaido-slides.png

Satellite images of slope failures in the Sapporo area of Japan following a typhoon and earthquake.
7.1.6 Gootee, B & Cook, J. (2020) Black Canyon Landslide, Annotated. Retrieved April 22, 2021 from https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/BlackCanyon_anno3_reduced_5.jpg?itok=ahySUJQK

Annotated image of Black Canyon Landslide, AZ
Table 7.1 Earle, S (n.d.) Retrieved April 22, 2021 from https://opentextbc.ca/physicalgeology2ed/chapter/15-2-classification-of-mass-wasting/#skiptable15.1

Table showing classification of slope failures based on type of material and type of motion.
7.2
7.2.1 Earle, S. Retrieved April 22, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/06/contribution-of-freeze-thaw-to-rock-fall.png

The process of freeze/thaw causing a rock fall.
7.2.2 AZGS (n.d). Retrieved April 22, 2021 from https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/rimrock%20rock%20fall%204-7-14.jpg?itok=NEiaHwYv

An image of a boulder smashed into the side of an RV in Verde Valley, AZ, after a rock fall.
7.2.3 USGS (n.d.) Retrieved April 22, 2021 from https://opengeology.org/textbook/wp-content/uploads/2016/07/10.4_Gros_Ventre-Cross-section.jpg

Cross-section of 1925 Gros Ventre slide showing sedimentary layers parallel with the surface and undercutting (oversteepening) of the slope by the river.
7.2.5 Earle, I (2010) Retrieved April 22, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/meager-rock-avalanche-2019-1024×753.png

Photograph of 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.
7.2.6 Earle, S. (n.d.) Retrieved May 3, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/depiction-of-the-contribution-of-freeze-thaw.png

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.
7.2.7 Earle, S. (n.d.) Retrieved May 3, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Pistol-Butt.jpg

An image of trees on a slope that is experiencing creep, notice the bent lower trunk.
7.2.8 Earle, S (n.d.) Retrieved May 3, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/motion-of-unconsolidated-sediments-in-an-area-of-slumping-1024×456.png

A depiction of the motion of unconsolidated sediments in an area of slumping.
7.2.9 Earle, S (n.d.) Retrieved May 3, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/slump-along-the-banks-of-a-small-coulee-near-Lethbridge.jpg

Photograph of 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.
7.2.10 Earle, S (n.d.) Retrieved May 3, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/lethbridge-2.png

A slump (left) and an associated mudflow (center)
7.2.11 Youberg, A (2016) AZGS Retrieved May 3, 2021 from
https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/Youberg-Huachucas-debrisflowfill.jpg?itok=Ba9LXOcg

Photograph of debris flow in cross section
7.3
NASA (2018) Landslide threats – NASA satellite data. Retrieved May 3, 2021 from
https://youtu.be/h7P55b8LJYU

Video showing how satellite data is used to predict landslides.
7.3.1 Conway, M. (2017) AZGS. Retrieved April 29, 2021 from
https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/Kitt%20Peak%20road%20cut-rockbolts.jpg?itok=2N7oUnUA

Photograph showing bolts used to keep rock face in place
ArizonaDOT (2014) US89 Landslide – Repair Begins (August 2014) Retrieved May 3, 2021
from https://www.youtube.com/watch?v=BUvQqiIDYLs

Video showing the damage and repair to the US 89 due to a landslide.

7.3.2 Earle, S (n.d.) Retrieved May 3, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/motion-monitoring-device-at-the-Checkerboard-Slide-near-Revelstoke.jpg

Photograph of part of a motion-monitoring device 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.
7.3.3 Topinka, L. (n.d.) USGS, Mount Ranier over Tacoma. Retrieved May 3, 2021 from https://commons.wikimedia.org/wiki/File:Mount_Rainier_over_Tacoma.jpg

Picture of Mount Ranier over Tacoma
Figure 7.3.4 A snow avalanche shelter on the Coquihalla Highway. The expected path of the avalanche is the steep un-treed slope above.

7.4
7.4.2 Burian, P. (n.d.) Gondola on the Grand Canal, Venice, Italy. Retrieved May 6, 2021 from https://upload.wikimedia.org/wikipedia/commons/6/6e/Gondola_on_the_Grand_Canal%2C_Venice%2C_Italy.jpg

Decorative Image of Venice canals
USGS (n.d.) The Science of Sinkholes. Retrieved May 6, 2021 from https://youtu.be/wubMuKDGBuk

Video explaining the science of sinkholes
7.4.2 Conway, M (2017) AZGS. McCauley Sinks, Holbrook, AZ. Retrieved May 6, 2021 from https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/McCauleysinks.jpg?itok=x7q58lZC

Aerial photograph of sinkholes