Fact Sheet 5.3: Earth Slope Stabilization

The mitigation objective of this Fact Sheet is to decrease the likelihood a landslide or earth movement will occur on a slope by improving slope stability.

Landslides generally are categorized as shallow or deep seated, which can determine their speed and size. Shallow landslides are rooted in the soil layer and often form slumps (depressions) along roadways or fast-moving debris flows down valleys. These types of landslides often are called "mudslides" by the news media. Shallow landslides also occur as flows (such as mudflows, earthflows, and debris flows), slides, or rockfalls and topples.

Deep-seated landslides are rooted in bedrock, often are slow moving, and can cover large areas and devastate infrastructure and housing developments. Deep-seated landslides usually occur as translational slides, rotational slides, or large block slides (see definitions below). Deep-seated landslides typically are much larger than shallow landslides (WA Geological Survey, 2017).

Definitions

Landslide—Movement of a mass of rock, debris or earth down a slope.

Debris Flow—Fast mass movement in which loose soil, rock and organic matter combine with water to form a slurry that flows downslope. Commonly called a "mudslide."

Earthflow—Generally occurs in fine-grained soil (e.g., silts and clays) when a disturbance causes the soil to lose its shear strength and liquefy. Earthflows can range from very slow (creep) to rapid and catastrophic.

Rotational Landslide—A landslide on which the surface of rupture is curved upward (spoon-shaped) and rotates around a line parallel to the ground surface and diagonal across the slide. (Figure 5.3.1)

Translational Landslide—A landslide in which the soil mass moves downward along a plane with little rotation or backward tilting. (Figure 5.3.1)

Block Landslide—A translational landslide in which the moving mass acts like one unit or several closely related units moving downslope together as one mass. (Figure 5.3.1)

Source: U.S. Geological Survey (USGS)

Slides

Slides are downslope movements of soil surface and can be deep-seated or shallow. The initiation of slides, like flows or rockfalls, is sensitive to steep slopes, the additional weight of water or other loads, and friction along their base.

Translational slides usually faily along geologica discontinuities such as faults, joints, bedding surfaces, or the contact between two rock types. They move out or down a planar surface with little tilting and can travel great distances. Translational slides can contain loose sediments or large slabs of bedrock.

Rotational slides (slumps) are landslides that occur along a curved or spoon-shaped surface. Backtilting may occur near the scarp of the landslide and there is often a toe of displaces material. Rotational slides occur because the internal strength of the material is overcome by its own weight. They are usually composed of relatively loose or consolidated material.

Block slides are a particular type of translational slide that occur when large and relatively intact slabs of rock or earth are rapidly transported downslope. These types of landslides can be large and damaging and occur where alternating layers of strong and weak rock slope downhill.

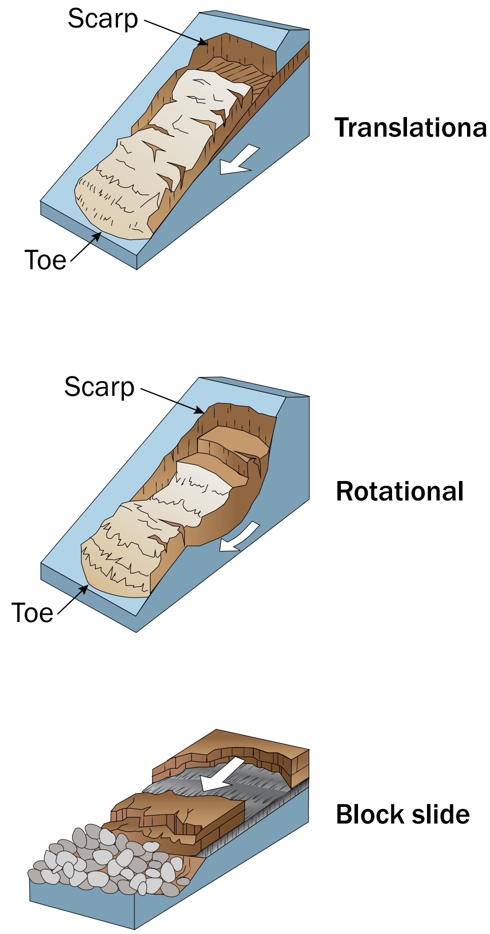


Figure 5.3.1. Examples and description of slides. (Source: Washington Geological Survey)

Figure 5.3.1 summarizes some common mitigation strategies that can improve the performance of earth slopes and decrease slide potential. These strategies are discussed in the sections that follow.

Table 5.3.1. Common Mitigation Solutions for Earth Slope Stabilization

Solutions and Options	***Shallow Failure***	***Deep Failure***
Mitigation Solution: Excavate		
Option 1: Remove or Replace Material at the Top of the Slope	✓	
Option 2: Build Benches or Terraces	✓	
Option 3: Reduce Slope Angle	✓	
Mitigation Solution: Reinforce or Strengthen		
Option 1: Install Geosynthetics	✓	✓
Option 2: Construct a Toe Buttress or Berm	✓	✓
Option 3: Conduct Deep Soil Mixing		✓
Option 4: Install Soil Nails		✓
Mitigation Solution: Install Drainage		
Option 1: Construct an Interceptor Trench	✓	
Option 2: Install Subsurface Drains	✓	✓
Option 3: Install Check Dams	✓	
Mitigation Solution: Install Retaining Walls		
Option 1: Install a Mechanically Stabilized Earth Wall		✓
Option 2: Install a Timber Pile Wall		✓
Option 3: Construct a Gabion Wall	✓	✓
Option 4: Construct a Crib Wall	✓	✓
Option 5: Construct a Bin Wall		✓
Mitigation Solution: Install Nature-Based Solutions		
Option 1: Use Natural and Hybrid Approaches	✓	

Mitigation Solution: Excavate

Excavation is used to remove material from the slope to lessen the forces that cause sliding. Generally, excavation is appropriate only for small slumps or shallow slides. The excavator should be kept a safe distance from the edge of the slope, so it does not add weight at the top of the slope, leading to slope instability. Do not remove the toe material at the bottom of the slope.

Option 1: Remove or Replace Material at the Top of the Slope

Removing soil from the top of the slope helps to reduce the downward pressure on the slope by reducing the weight of the overlying soil, which helps improve stability (Figure 5.3.2).

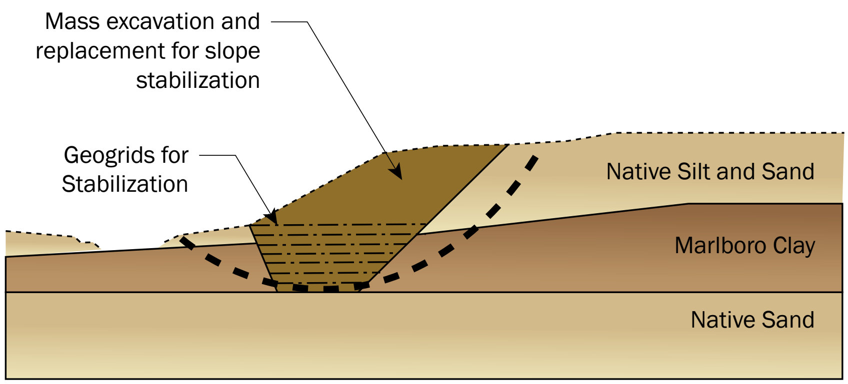
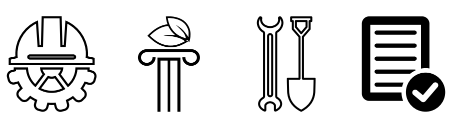


Figure 5.3.2. Removing soil and replacing it with lightweight fill can help decrease loads that drive soil downslope.

When evaluating this option, keep these considerations in mind:

- The soil removed should be placed away from the slope and/or trucked offsite. The removed soil may be replaced with lightweight fill.
- This option may be appropriate for rotational-type landslides, but it should not be used for translational slides or debris-flow landslides (USGS, 2008).

CONSIDERATIONS:



Option 2: Build Benches or Terraces

Benching involves making a series of stair-step cuts into the slope to reduce the slide-driving forces (Figure 5.3.3). It also can be used to cut a large slope into smaller slopes that can be mitigated individually.

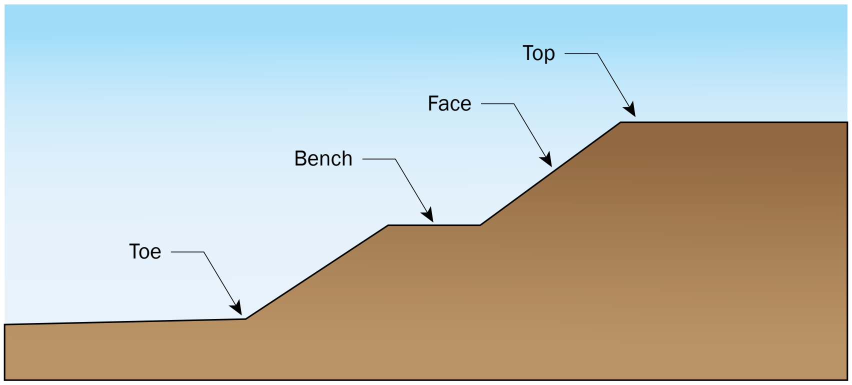
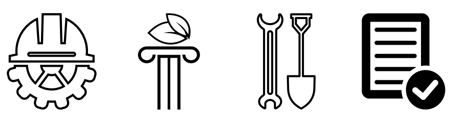


Figure 5.3.3. Benching or terracing can help improve slope stability.

When evaluating this option, keep these considerations in mind:

- The flat surfaces of the benches can be used to control surface drainage or install other structures such as drainage pipes or retaining walls.
- Benching can help address shallow slope failures but is not effective for deeper failure surfaces.

CONSIDERATIONS:



Option 3: Reduce Slope Angle

Steep slopes can have an increased risk of instability (Figure 5.3.4). Reducing the slope angle of the ground surface while also removing some of the driving force can improve slope stability.

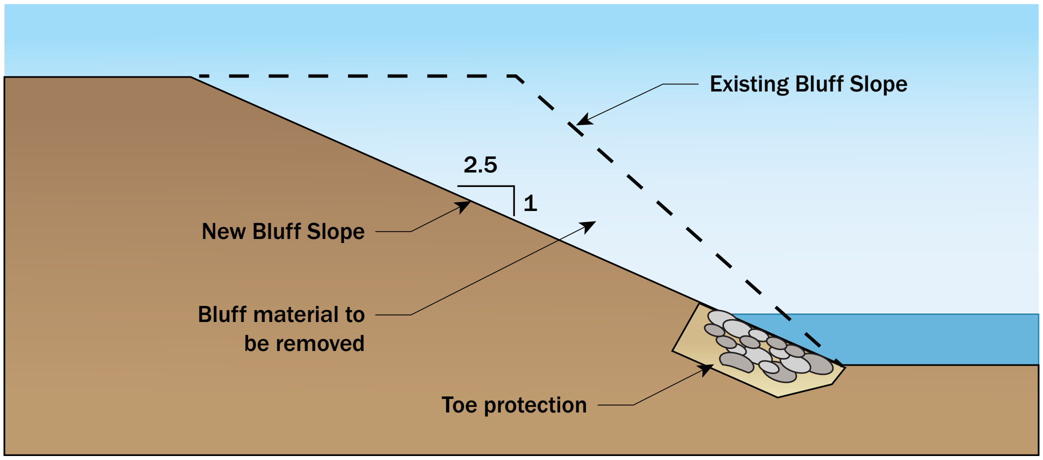
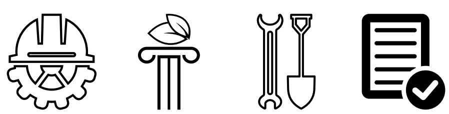


Figure 5.3.4. Reducing the slope angle removes some of the driving forces that can cause instability. (Source: USGS, 2004)

When evaluating this option, keep these considerations in mind:

- Smoothing the slope surface while reducing the slope angle also can help improve surface drainage.
- This approach is effective only for small slumps and shallow slides.

CONSIDERATIONS:



Mitigation Solution: Reinforce or Strengthen

The shear strength of soil, which is a combination of friction and bonding between particles, is what resists downward movement of the soil along a slope. Increasing the shear strength of soil helps it withstand sliding. There are several common methods of strengthening soil to improve sliding resistance.

Option 1: Install Geosynthetics

Geosynthetics generally are flat, manmade materials used to improve the strength of soil and rock through reinforcement. Reinforced soil slopes are constructed by placing alternating layers of a specified thickness of compacted soil and geosynthetic (Figure 5.3.5). Reinforced soil slopes usually are constructed under two conditions: (1) to improve stability during reconstruction of a slope that already has failed, or (2) to improve stability at the edges of a slope.

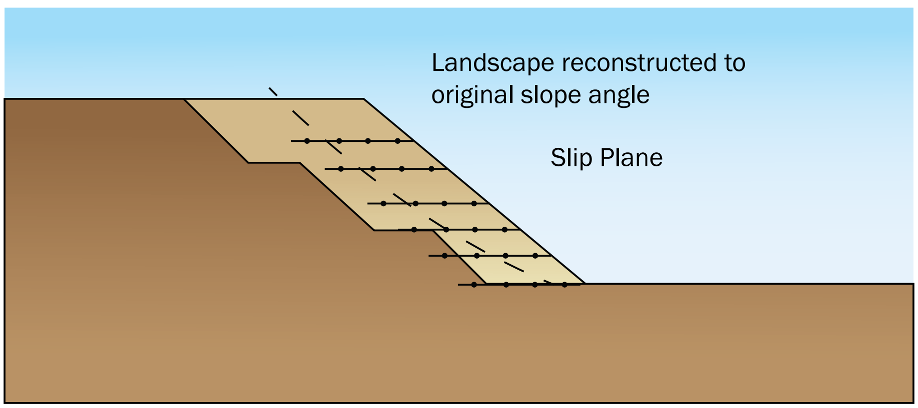
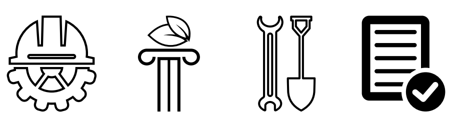


Figure 5.3.5. Geosynthetics can be used to reinforce and strengthen slopes. (Source: FHWA, 2009)

When evaluating this option, keep these considerations in mind:

- Reinforcement allows the slope to be constructed at a steeper angle than would be safe when placing the soil alone. Where space is restricted or to create additional space for road shoulders and lanes, slope angles can be up to 70 degrees.
- Use geosynthetics to help increase drainage within the slope.

CONSIDERATIONS:



Option 2: Construct a Toe Buttress or Berm

Build a toe buttress or berm is built by adding compacted soil along the bottom of the slope to provide extra resistance against material sliding on the slope (Figure 5.3.6).

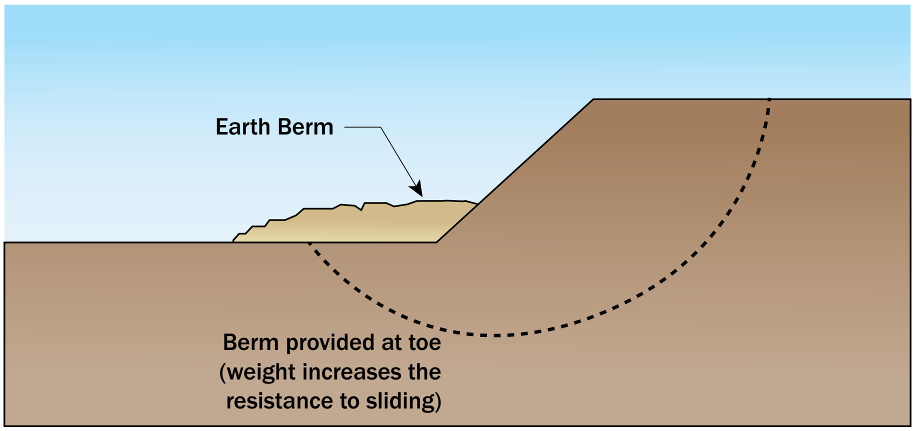
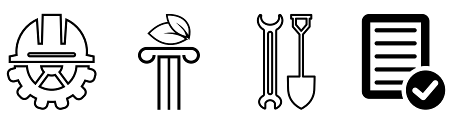


Figure 5.3.6. A toe berm adds resistance to sliding material.

When evaluating this option, keep these considerations in mind:

- While any material can be used to build the berm, freely draining material such as sand allows water to flow and not build up along the slope. Water build-up within the slope can increase the chances of a landslide occurring.
- Use this option for all slide types (shallow and deep).

CONSIDERATIONS:



Option 3: Conduct Deep Soil Mixing

Deep soil mixing (DSM) involves mixing a chemical stabilizer such as cement or lime with soil in place on the slope. Mixing is done using a long tool with a hollow shaft and blades or paddles mounted on a drill rig. Typically, the tool is drilled into the ground to the required depth and then the chemical stabilizer is added as the tool is slowly pulled out (Figure 5.3.7).

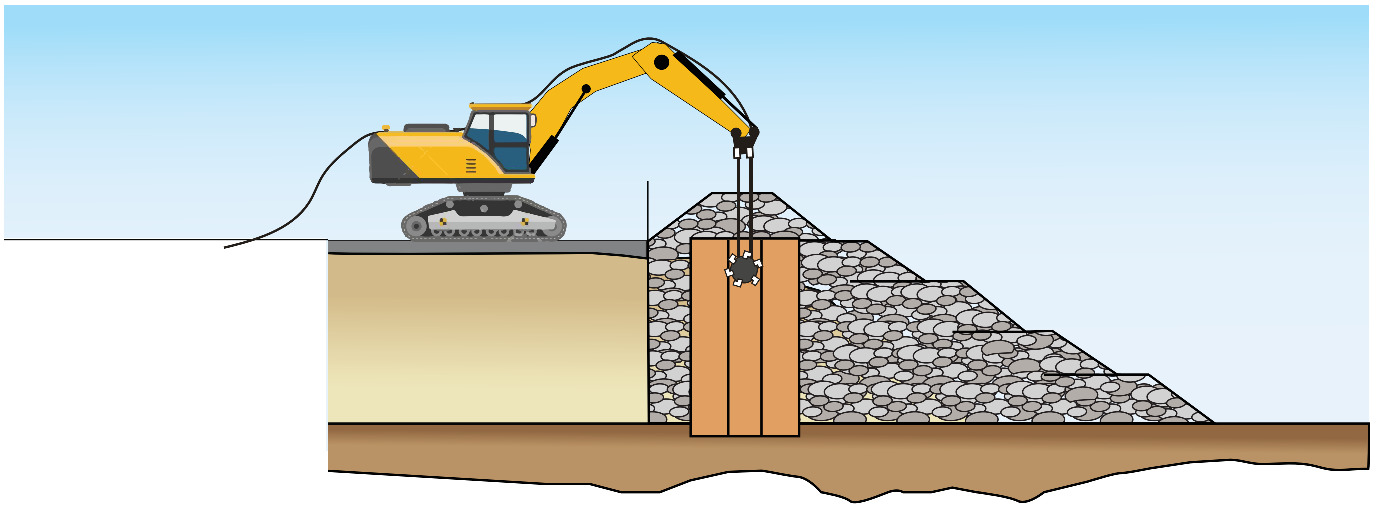
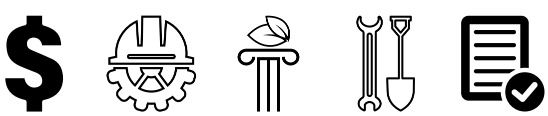


Figure 5.3.7. Deep soil mixing (DSM) creates a soil-concrete column to provide additional stability against sliding.

When evaluating this option, keep these considerations in mind:

- DSM can be wet or dry.
  - Wet DSM involves mixing the soil with a wet slurry to create a soil-concrete column. When using wet mixing, add the slurry through the hollow shaft while the drilling tool is penetrating the soil.
  - Dry DSM involves blending wet soil with a dry binding material to create a soil column.
- Both wet and dry DSM methods result in a soil column that has increased shear strength and stiffness.
- Arrange a series of individual columns to resist the driving forces of the slope.
- Soil mixing typically is used in soft soils for stabilization purposes.
- Use DSM to lessen the potential for deep slides.

CONSIDERATIONS:



Option 4: Soil Nailing

Typically, soil nails are steel rods or bars that are installed with cement grout into a slope at an angle (Figure 5.3.8). Usually, the nails are inserted into pre-drilled holes, but other methods, including driving, self-drilling, launching, and jet-grouting, can be used. A grouting material such as concrete is used to fill the hole around the nail. The grout protects the nail from corrosion while also providing additional resistance to sliding of the surrounding soil.

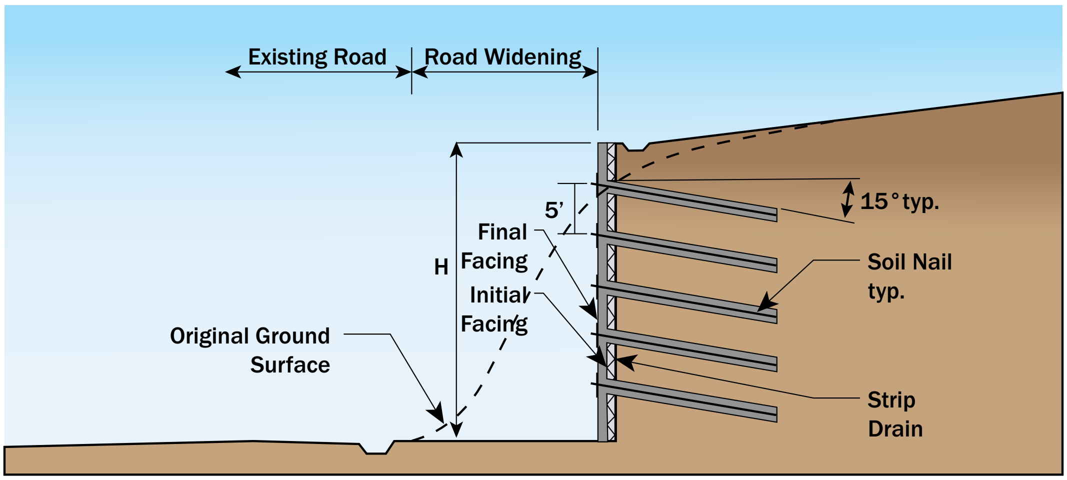


Figure 5.3.8. Soil nailing can allow slope stabilization at steep angles. (Source: FHWA, 2015)

When evaluating this option, keep these considerations in mind:

- Use additional corrosion protection measures, such as galvanization or epoxy coating, to further protect the nails.
- Apply a facing to the surface of the nailed slope to help improve stability of the soil between the nails and provide erosion protection. While reinforced concrete, shotcrete, or precast panels typically are used for the facing of soil nail walls, softer materials such as mesh can be used on slopes so that vegetation can be established (Figure 5.3.9).

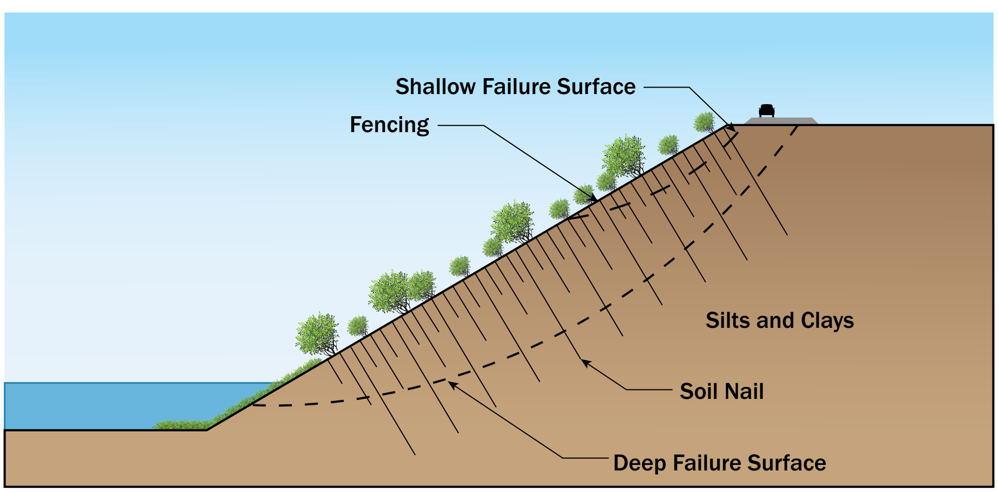
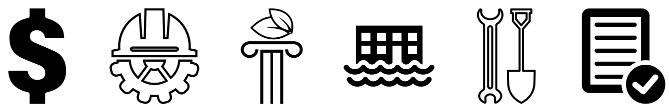


Figure 5.3.9. Soil nailing can be combined with vegetation to improve slope stability and aesthetics for both shallow and deep failure surfaces. (Source: FHWA, 2015)

- Attach a bearing plate to the nail over the surface of the facing, and if concrete facing is being used, apply additional facing to permanently cover the bearing plate and nail head.
- Use soil nailing to lessen the potential for deep slides.

CONSIDERATIONS:



Mitigation Solution: Install Drainage

Water is a key element that contributes to the stability or instability of a slope. The weight of water adds weight to the slope, which increases the forces driving soil down the slope and can decrease stability. Water also can dissolve binding agents that hold soil or sediment particles together, which reduces the bond between particles and can lead to decreased stability. In addition, water can act as a lubricant between an overlying well-drained soil (sand and gravel) and an underlying poorly drained soil (clay and silt). In this situation, the water drains more quickly through the well-drained soil and accumulates along its interface with the poorly drained soil since water cannot enter the poorly drained soil as quickly. Improving drainage within a slope can help to improve slope stability.

Option 1: Construct an Interceptor Trench

An interceptor trench is a drainage system installed near the top of a slope or above the top of a known slide area to collect and direct surface water and subsurface water from within soil layers away from the slope (Figure 5.3.10). Reducing the amount of water on and within a slope helps to decrease the driving weight at the top of the slope and helps to reduce the risk of erosion.

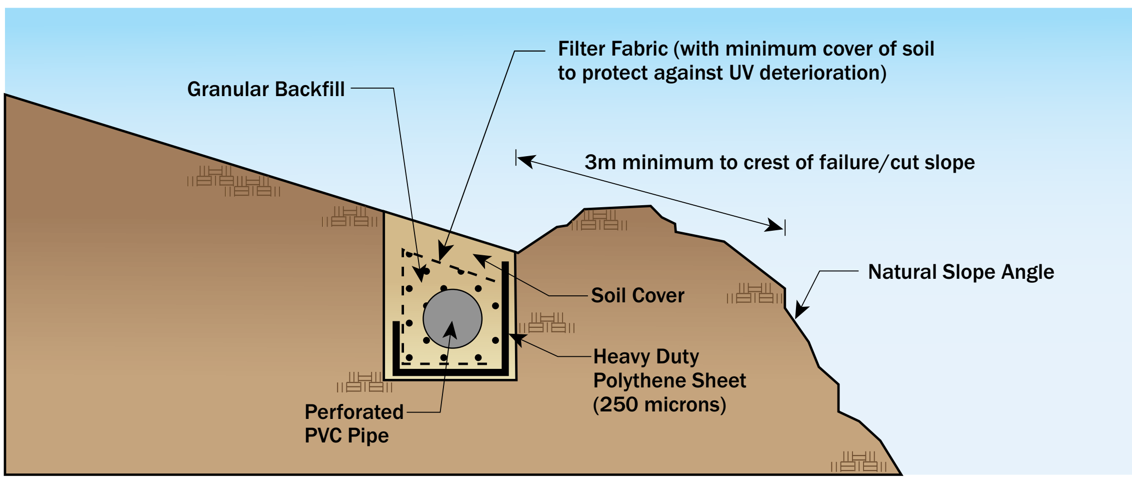


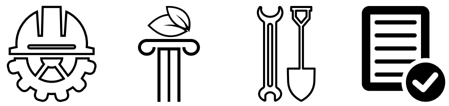
Figure 5.3.10. Interceptor trench drains can be used to direct surface runoff away from slopes.

Some things to consider when evaluating this option include:

- Use freely draining material, usually clean gravel, as backfill to help prevent the perforated pipe from clogging. Add a geotextile filter fabric to further prevent clogging.
- Hydraulically connect the trench to another pipe or to a drainage ditch or spillway to direct the water down the slope at a controlled location.
- Use this approach for slopes with shallow slide potential and on terraced slopes, where a trench drain is installed at the base of each terrace step. Deeper trenches can be constructed but must comply with worker safety requirements.

- Combine this approach with other measures, such as subsurface drains discussed below, to increase effectiveness.

CONSIDERATIONS:



Option 2: Install Subsurface Drains

Subsurface drains are perforated pipes that are inserted into the slope at set elevations and spacings (Figure 5.3.11). The idea is to lower the water table to the level of the lowest pipe, which decreases the driving forces by decreasing the water content of the slope soils.

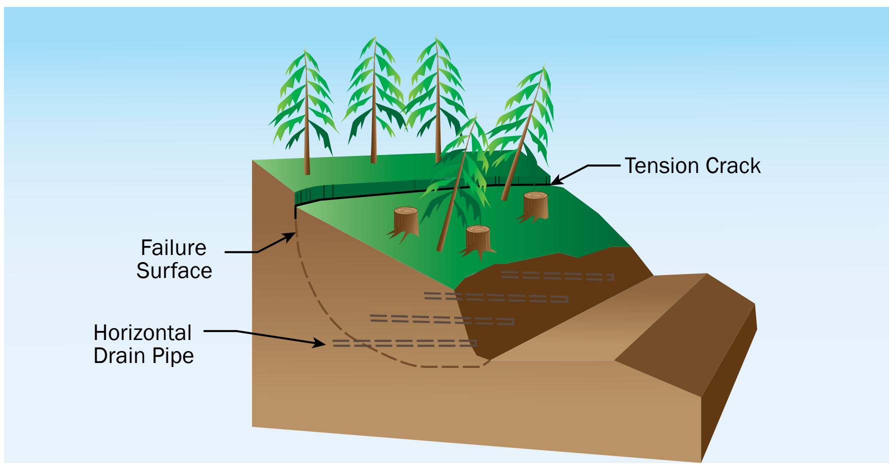
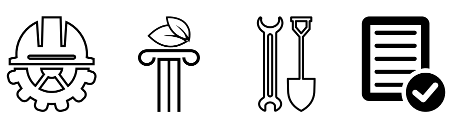


Figure 5.3.11. Horizontal drains help lower the water table, which reduces driving forces by decreasing soil water content. (Source: USGS, 2008)

When evaluating this option, keep these considerations in mind:

- Slightly slope the drains to drain down from the top of the drain inside the slope to the pipe exit above ground.
- If a well-drained soil overlies a poorly drained soil, install the drain to intercept water near the interface of the two layers. This helps reduce the likelihood that water will accumulate at the interface causing the overlying layer to slide along the underlying layer.
- Use subsurface drains to mitigate slopes with both shallow and deep failure surfaces.

CONSIDERATIONS:



Option 3: Construct Check Dams

A check dam is built across a drainage ditch to slow the flow of water and reduce erosion (Figure 5.3.12). Check dams usually are built with rock, but also can be made from wattles, fiber rolls, sand or gravel bags, logs, or manufactured systems.

Check Dams

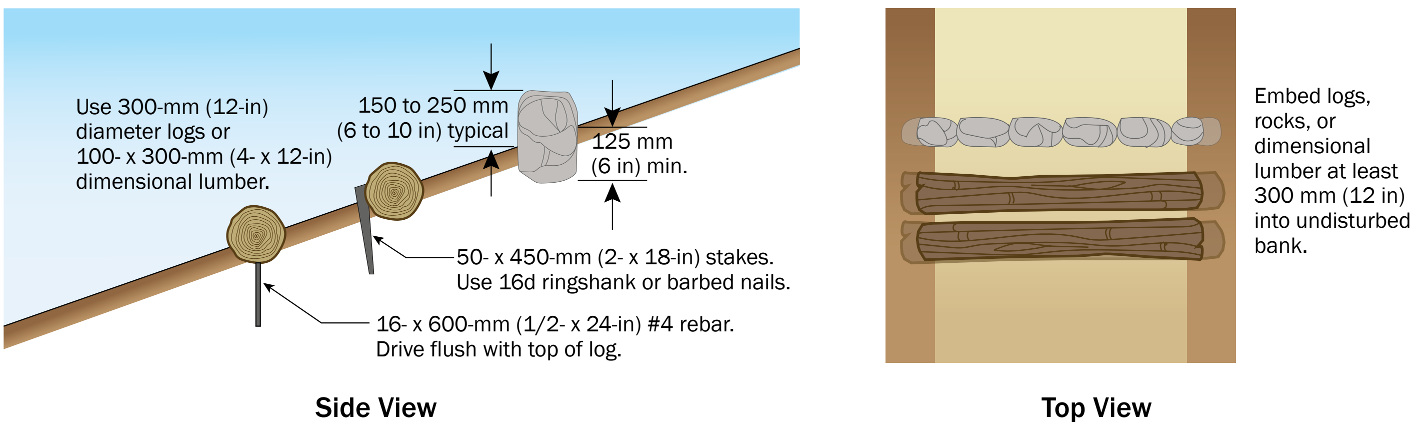
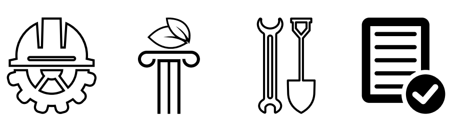


Figure 5.3.12. Check dams can be constructed of logs, rocks, or other materials to slow the flow of water in a channel on a slope. (Source: U.S. Forest Service, 2007)

When evaluating this option, keep these considerations in mind:

- Use check dams with interceptor trenches to direct the flow of water down a slope to a location where the water is collected and/or released.
- A series of check dams can control the flow of water more effectively than a single check dam.
- The check dam should completely span the width of the channel to prevent washout.
- Check dams can be effective for slopes with shallow slide potential.

CONSIDERATIONS:



Mitigation Solution: Install Retaining Walls

Retaining walls are relatively rigid structures that can help strengthen soil and increase resistance to sliding forces in areas where space is limited. They also can be used to create additional space, such as for road shoulders or parking areas. Retaining walls must be designed to so they will not overturn, slide, or dislodge from extreme foundation pressure or water uplift. Local zoning, permitting, or code requirements might require a wall to be designed by a licensed Professional Engineer.

Option 1: Install a Mechanically Stabilized Earth Wall

Mechanically stabilized earth (MSE) walls are built using compacted granular soil backfill and geotextiles in alternating layers to make a steep slope that then has a wall facing applied (Figure 5.3.13). The stability of the wall comes from the friction that acts between the compacted soil backfill and the geotextile material. The wall facing is relatively thin; it helps hold the layers in place and allows the wall angle to be steep—usually from about 70 degrees up to even vertical (90 degrees).

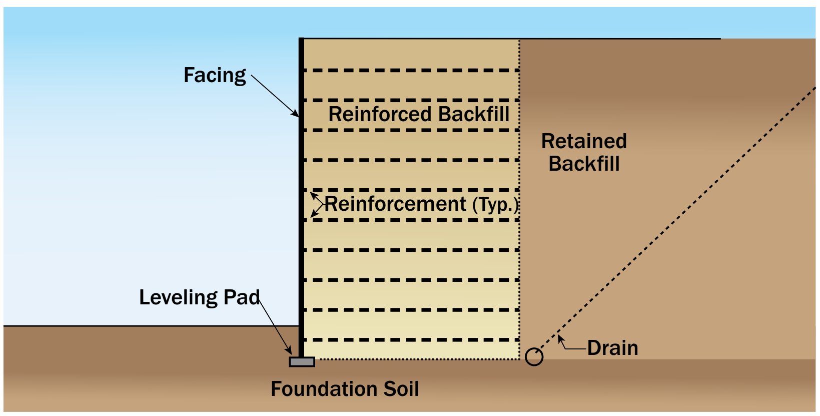
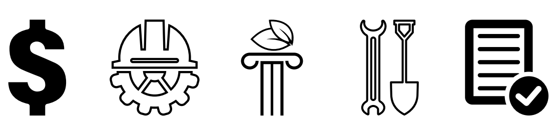


Figure 5.3.13. MSE walls use geotextiles and granular soil backfill to retain slopes. (Source: FHWA, 2009)

When evaluating this option, keep these considerations in mind:

- The facing must be able to withstand erosion and corrosion.
- MSE walls can be built quickly and are resistant to forces such as earthquakes.
- MSE walls also must be a minimum width to provide enough stability.
- Use MSE walls to protect against deep-seated slides.
- MSE walls are used commonly in highway projects for bridge abutments and wing walls, but also can be used for other purposes, such as containment structures around oil and gas tanks.

CONSIDERATIONS:



Option 2: Install a Soldier Pile Wall

Soldier pile walls use a system of steel piles driven vertically at regular intervals (usually every 6 feet to 12 feet) and horizontal planks, called lagging, placed between the piles to retain the soil behind the planks (Figure 5.3.14). Soldier pile walls provide stability by resisting the sideways forces of the soil behind the wall. The piles are usually steel H-piles, but can include precast concrete, micropiles, and conventional pipe sections (Pilebuck, March 2019). The lagging material usually consists of wood planks but also can be metal decking or precast concrete. The piles are installed and then excavating occurs in stages to place the lagging until the design wall height is reached. This type of retaining wall should be designed by a Professional Engineer.

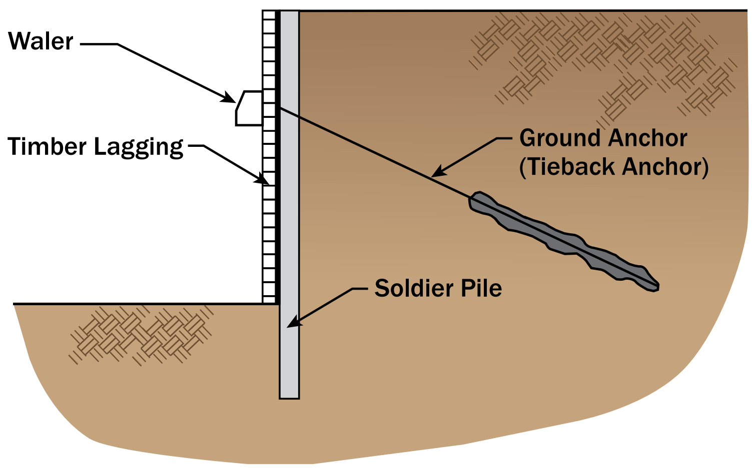
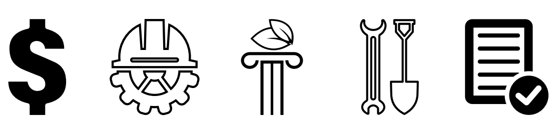


Figure 5.3.14. Soldier pile walls can be used to reinforce failure planes. (Source: FHWA, 1999)

When evaluating this option, keep these considerations in mind:

- The empty space behind the wall lagging is filled with compacted soil. If backfilling is not completed properly, settlement behind the wall can occur.
- Soldier pile walls can be designed as cantilevered walls up to a certain height, above which steel tiebacks can be drilled and grouted into the retained soil as shown in Figure 5.3.14.
- If the retaining wall is permanent, consider applying a shotcrete facing.
- Soldier pile walls are difficult to construct where a high-water table exists; complete dewatering first.
- Installation of soldier pile retaining walls in soft soils can be difficult.
- Use soldier pile walls generally to provide resistance to deep-seated slides.

CONSIDERATIONS:



Option 3: Construct a Gabion Wall

A gabion is a wire cage filled with rocks, concrete pieces, gravel, or bricks (Figure 5.3.15). Gabion walls provide stability by resisting lateral forces behind them. Because gabion walls typically are filled with rocks, they are freely draining and do not allow a buildup of water behind the wall.

Typically, a gabion is shaped like a box or a cylinder. For soil retention purposes, a gabion will be rectangular. For dams or foundation construction, cylinder-shaped gabions typically are used. The wire used to build a gabion basket usually is stainless steel, PVC-coated steel, or galvanized steel. The wire should be corrosion resistant. The filled wire boxes are stacked in rows to create a wall. The rows might have a slight step-back or might be placed directly on top of each other to create a vertical face. The rows are tied together with wire. A bastion is a gabion that is lined with a geotextile and filled with sand.

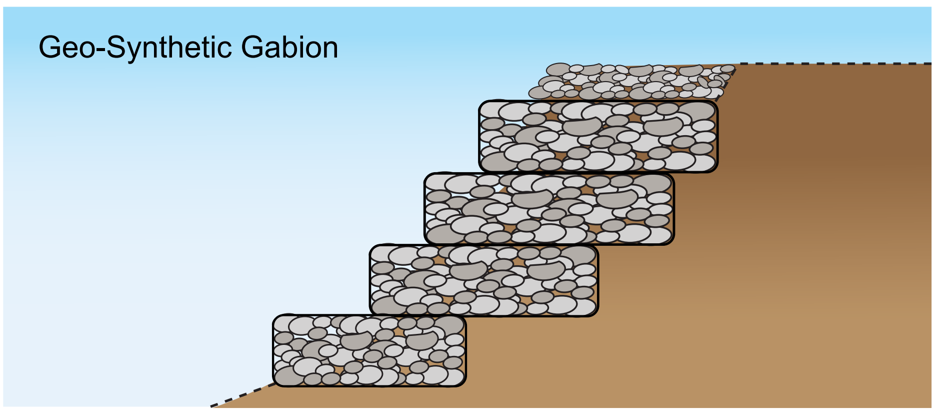
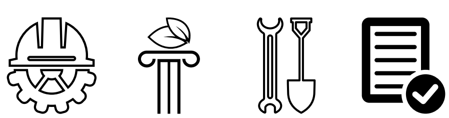


Figure 5.3.15. Gabions can be used to improve slope stability by resisting the sideways forces behind them. (Source: FHWA, 2001)

When evaluating this option, keep these considerations in mind:

- Depending on local zoning, permitting, and code requirements, gabion walls exceeding a certain height might need to be designed by a Professional Engineer.
- Gabions can get clogged by debris and soil, requiring maintenance. They also can become habitats for small animals.
- Gabion walls can protect against shallow or deep failure potential.

CONSIDERATIONS:



Option 4: Construct a Crib Wall

A crib wall is a gravity wall system consisting of stacked elements that are filled with soil or rock (Figure 5.3.16). Typically, precast concrete parts are used to build the walls, although preservative-treated timber also can be used. Crib walls are constructed like log cabins. Elements called headers are set perpendicular to the wall face. Elements called stretchers are interlocked with the headers to form the wall face. Headers and stretchers are stacked alternately to form a gravity retaining wall. Crib wall elements can be stacked vertically but usually are sloped back. The area behind the crib wall is backfilled with freely draining, compacted soil or rock.

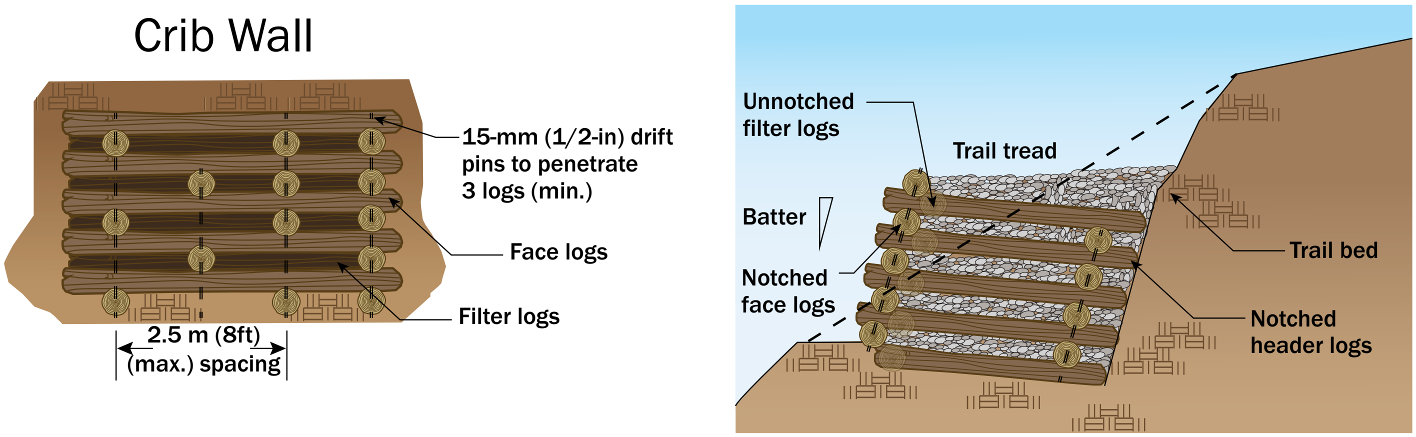
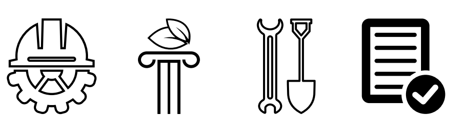


Figure 5.3.16. Crib walls can be constructed easily to retain soil on a slope. (Source: U.S. Forest Service, 2007)

When evaluating this option, keep these considerations in mind:

- Securely attach, bury or anchor the toe of the crib wall for it to be effective; otherwise, the wall can fail.
- Use higher walls by building deeper cribs or by building additional cribs terraced or staggered behind the front crib.
- Crib walls can accommodate curves along roads, parking areas, etc., and can be covered with plant materials to make them more aesthetically pleasing.
- Use crib walls to protect against shallow or deep failure potential.

CONSIDERATIONS:



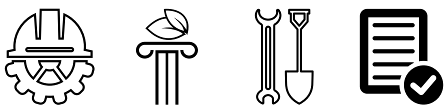
Option 5: Construct a Bin Wall

Bin walls are gravity wall systems like crib walls, but interlocking bins are stacked on top of each other and backfilled with granular soil. The bins typically are made from steel or concrete and are bolted together.

When evaluating this option, keep these considerations in mind:

- The design of these walls should meet minimum embedment requirements.
- Depending on the environment, metal bin walls may be subject to corrosion.
- Use bin walls to protect against shallow or deep failure potential.

CONSIDERATIONS:



Mitigation Solution: Install Nature-Based Solutions

Option 1: Use Natural and Hybrid Approaches

Using natural materials to protect against soil movement is referred to as nature-based solutions or natural infrastructure. Hybrid approaches, which use a combination of living and non-living materials, can be used to protect slopes against erosion and improve the stability of upland slopes against shallow failures (Figure 5.3.17).

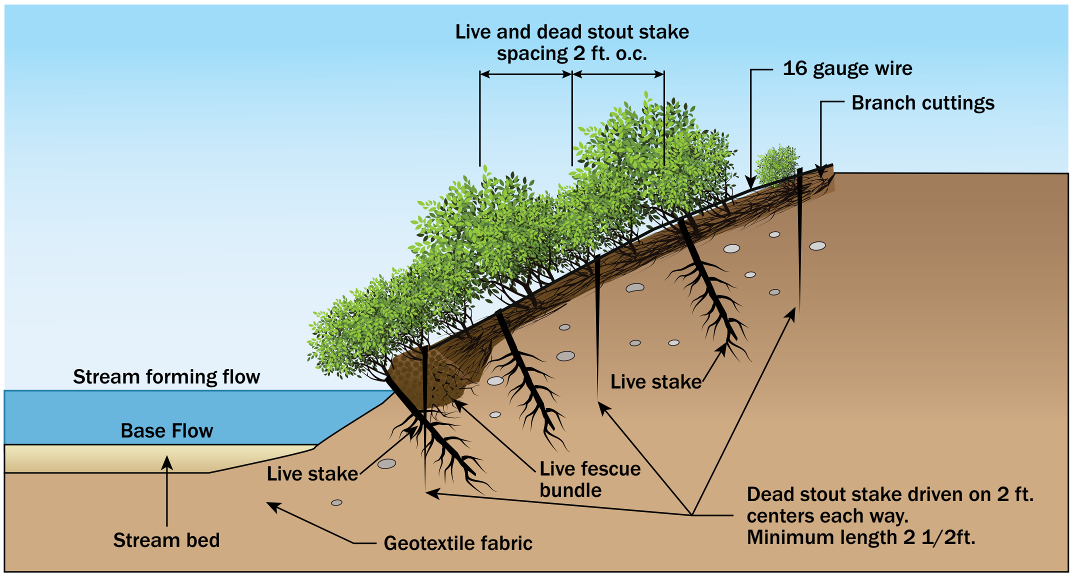


Figure 5.3.17. Using vegetated stakes alone or in combination with a brush mat can help control erosion on slopes. (Source: NRCS, 1996)

When evaluating this option, keep these considerations in mind:

- Use nature-based solutions alone or in conjunction with other slope stabilization methods.
- Use surface coverings, such as seeding, hydroseeding, transplanted vegetation and mulch, to protect against wind and water erosion.
- Use live plantings, alone or in combination with crib walls or gabion walls, to improve slope stability.
- As seen in Figure 5.3.18, live plantings such as stakes and fascines can help to reinforce the soil and withstand soil movement through interconnected root systems. Stout stakes are live but dormant woody cuttings with the branches removed. Fascines or wattles are living branches bundled together to trap sediment and protect against erosion. They are laid horizontally along streambanks to decrease stream velocity and reduce erosion.

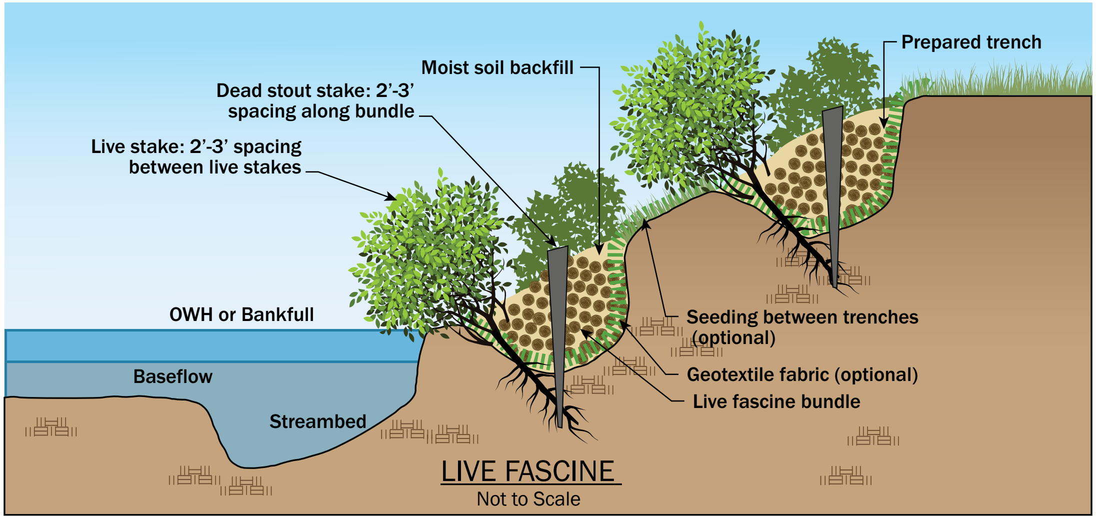


Figure 5.3.18. Live fascine bundles can be used with stakes to help control erosion. (Source: USDA Forest Service, 2006)

- Use stakes in combination with brush mattresses to provide erosion control and improve slope stability.
- Live plantings placed among gabion walls or crib walls can help to reinforce the fill and improve the appearance of those structures.
- Use vegetative plantings in small areas where accessibility is an issue to improve aesthetics (Figure 5.3.19).
- Plantings can be installed only during dormant seasons, and some planting methods can be labor intensive.
- Some plantings require regular maintenance, such as fertilization and watering, until they are well established.

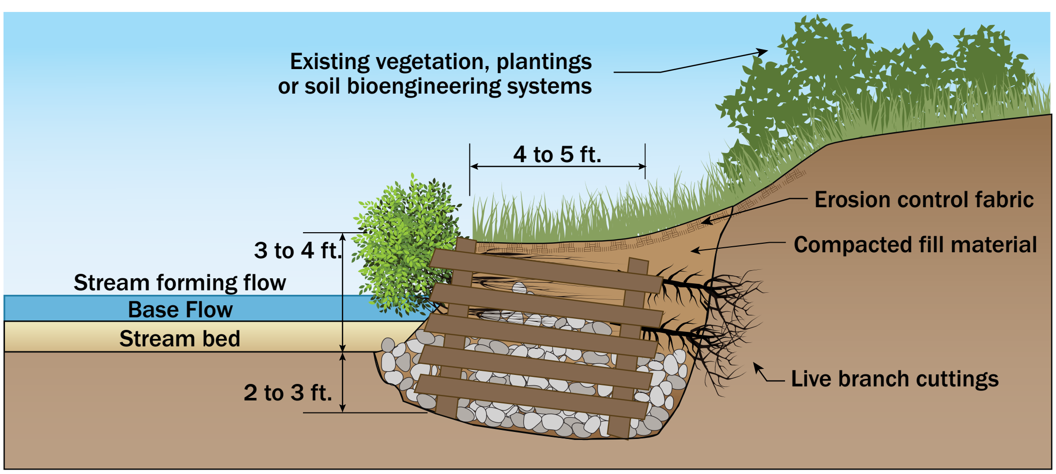
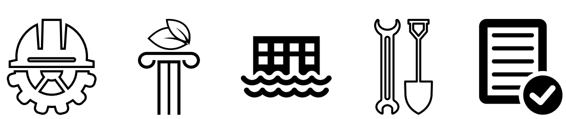


Figure 5.3.19. Live crib walls can provide stability and help control erosion. (Source: NRCS, 1996)

CONSIDERATIONS:



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More detailed information about landslides, their causes, and potential mitigation strategies can be found in these publications. This list is not exhaustive, but it provides some information that can be used for decision-making and design.

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