Fact Sheet 2.3: Mitigation of Dams and Reservoirs

The mitigation objective of this Fact Sheet is to improve safety and resilience by rehabilitating dams and reservoirs to improve issues with stability, water control and erosion.

- Dams are a critical part of the nation's infrastructure, providing water supply, hydropower, flood control and other benefits. To lessen potential disastrous effects from floods and hurricanes, having a better understanding of an area's precipitation conditions and changes in downstream populations over the life of the dam can improve key decision making. Rehabilitating dams to meet the newest technical standards and other factors that may impact dam safety is essential.
- Selection of the best mitigation measures for dams may depend on certain limitations. For example, the availability of land for expansion, availability of materials, and restrictions on downstream release volumes may influence which options are chosen.

Dam Hazard Potential Classifications

It is important to understand a dam's hazard potential classification before choosing mitigation options. Dams are rated according to their hazard potential, which is "the possible adverse incremental consequences that result from the release of water or stored contents due to failure of the dam or mis-operation of the dam or appurtenances" (FEMA, 2004). Downstream consequences may occur during operation of the dam when floodwater is released through spillways and outlet works or when water is released by partial or complete failure of the dam. Consequences may also occur in the area upstream of the dam because of backwater flooding or the effects of landslides around the reservoir perimeter. Dam hazard potential classifications are important to know because the hazard potential classification may impact the mitigation solution.

Low Hazard Potential: Dams where the failure or mis-operation results in no probable loss of human life and low economic and environmental issues (Figure 2.3.1).

Significant Hazard Potential: Dams where failure or mis-operation results in no probable loss of human life, but it could cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

High Hazard Potential: Dams whose failure or mis-operation results in probable loss of human life (Figure 2.3.2).

Figure 2.3.1. This dam is considered low hazard potential because, if it failed, it would only impact the forest around it. (Source: Library of Congress, Prints & Photographs Division, photograph by Carol M. Highsmith, LC-DIG-highsm-08052)

Figure 2.3.2. This dam is considered high hazard potential because its failure would impact the community directly downstream and could result in loss of life and property. (Source: NRCS, 2014)

Table 2.3.1 briefly summarizes some common mitigation strategies and briefly describes them in subsequent sections.

Table 2.3.1. Common Mitigation Solutions for Dams and Reservoirs

Solutions and Options	***Earth Embankment Dams***	***Concrete or Masonry Dams***	***Riser or Conduit Spillways***	***Mass Concrete Ogee Spillways***	***Structural or Armored Spillways***	***Grassed Spillways***
Mitigation Solution: Improve Stability						
Option 1: Reduce the Slope Angle	✓					
Option 2: Use Buttressing	✓					
Option 3: Use Anchoring		✓		✓		
Mitigation Solution: Increase Spillway Capacity						
Option 1: Expand Existing Spillway			✓	✓	✓	✓
Option 2: Add New Spillway			✓	✓	✓	✓
Mitigation Solution: Increase Temporary Storage Capacity						
Option 1: Raise the Dam Height	✓	✓				
Mitigation Solution: Control Surface Erosion						
Option 1: Use Armoring	✓					✓
Option 1: Build a Parapet Wall	✓	✓				
Option 2: Build a Cutoff Wall to Address Headcutting	✓					✓

Solutions and Options	***Earth Embankment Dams***	***Concrete or Masonry Dams***	***Riser or Conduit Spillways***	***Mass Concrete Ogee Spillways***	***Structural or Armored Spillways***	***Grassed Spillways***
Mitigation Solution: Reduce Seepage and Internal Erosion						
Option 1: Install a Blanket Drain	✓					
Option 2: Install a Filter Diaphragm	✓		✓			
Option 3: Install a Reverse Filter	✓					✓
Option 4: Install a Seepage Cutoff Wall	✓					✓
Mitigation Solution: Address Foundation Issues						
Option 1: Install a Grout Curtain	✓					
Option 2: Install a Foundation Cutoff Wall	✓					

Non-Structural Mitigation for Safety of Dams and Reservoirs

Resources for non-structural mitigation and resilience measures for dams and reservoirs may be found at the Association of State Dam Safety Officials (ASDSO) website (www.damsafety.org).

Importance of Emergency Planning for Dams

When people live in an area that could be affected by the operation or failure of a dam, there is the potential for a dam safety incident. Development of Emergency Action Plans (EAP) and Emergency Operations Plans (EOP) help dam owners, emergency management officials and other stakeholders work together to protect lives and reduce property damage associated with dam safety incidents.

Dam Safety Incident: An impending or actual sudden uncontrolled release or excessive controlled release of water from an impounding structure occurs.

Option 1: Develop Emergency Action Plan

Each high hazard potential or significant hazard potential dam should have an EAP. An EAP is a formal document that identifies potential emergency conditions at a dam and specifies actions to be followed to minimize loss of life and property damage. The EAP includes:

- Actions the dam owner will take to moderate or alleviate a problem at the dam
- Actions the dam owner will take, and in coordination with emergency management authorities, to respond to incidents or emergencies related to the dam
- Procedures dam owners will follow to issue early warning and notification messages to responsible downstream emergency management authorities
- Inundation maps to help dam owners and emergency management authorities identify critical infrastructure and population-at-risk sites that may require protective measures, warning, and evacuation planning
- Delineation of the responsibilities of all those involved in managing an incident or emergency and how the responsibilities should be coordinated

Specific guidance on Emergency Action Plans is available in FEMA P-64, *Federal Guidelines for Dam Safety: Emergency Action Planning for Dams.*

Option 2: Develop Emergency Operations and Response Plans

Any community that is potentially impacted by dam safety incidents should develop emergency operations plans (EOPs). They should develop, maintain and implement the emergency operations plan in collaboration with community officials; state, local, tribal, and territorial emergency managers; and other key stakeholders who maintain responsibilities during a dam safety emergency.

When evaluating this option, keep these considerations in mind:

- Identify the inundation zone and any other areas that could be impacted by dam operation or a dam safety incident. Also identify impacts to other infrastructure (utilities, transportation networks, etc.) to be able to plan response and recovery activities accordingly.

- Create a chart of key contacts to carry out emergency notification and coordination procedures. As multiple jurisdictions may be impacted by a dam incident, advance coordination of the jurisdictions is highly recommended.
- Address dam incidents in an annex to the emergency operations plan or comprehensive emergency management plan, in an appendix to other base planning products, or in a stand-alone dam incident plan. Emergency managers should choose the option that aligns to their planning architecture.
- Develop procedures for public evacuation that include evacuation routes and emergency shelter locations that meet the needs of the community.
- Encourage dam owners and operators to communicate with residents and businesses whose properties could be impacted by a dam safety incident.

Specific guidance on Emergency Operations Plans is available in FEMA's *Emergency Operations Planning: Dam Incident Planning Guide, Dam Safety Collaborative Technical Assistance.*

Mitigation Solution: Improve Stability

A dam must be stable and well maintained. If not, a slope failure or other condition can damage it, making it unreliable to withstand flood conditions. Failing slopes can lead to structure instability and dangerous consequences. Figure 2.3.3 shows an example of a failed slope.

Figure 2.3.3. Example of failed downstream slope. (Source: U.S. Forest Service, 2012)

Option 1: Reduce the Slope Angle

One way to improve the stability of an earth embankment dam is to reduce (flatten) the unstable slope angle (Figure 2.3.4). The appropriate slope angle should be chosen based on a slope stability analysis using current standards of practice and applying the latest regulations.

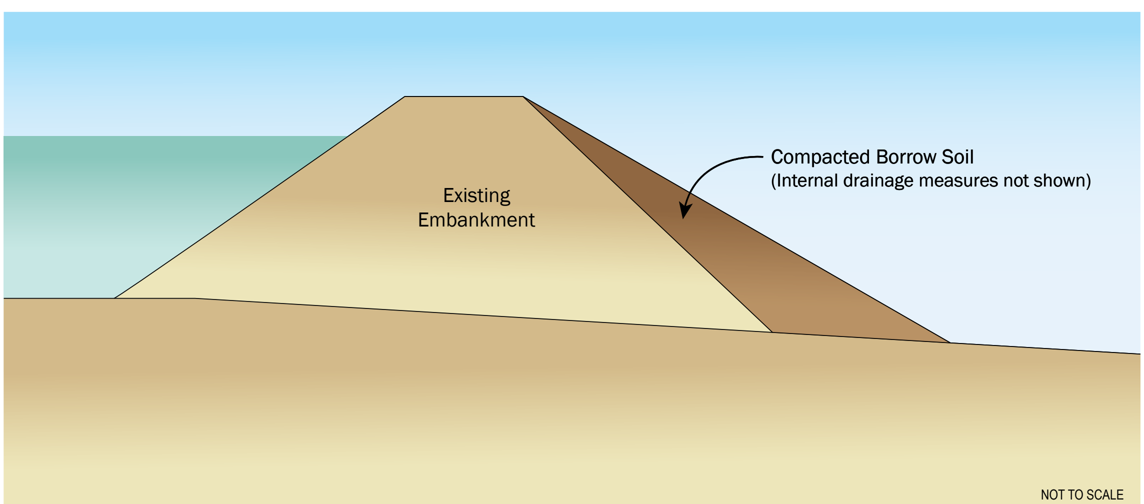


Figure 2.3.4. Use of compacted fill to reduce the downstream slope angle.

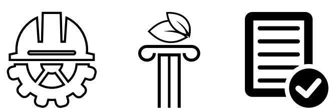
When evaluating this option, keep these considerations in mind:

- This option requires additional space downstream of the dam.
- An inclined chimney drain and downstream blanket drain can be added into the design by an engineer to handle seepage.

Seepage: The internal movement of water that may take place through the dam, the foundation or the abutments.

- There are additional considerations for upstream slope reduction. If downstream land is not available, another option is to drain the reservoir or build a temporary upstream cofferdam to hold the water and allow construction of a flatter slope in the upstream direction. When evaluating this option, keep these considerations in mind:
- Expanding the embankment in the upstream direction likely would require additional foundation work.
- This approach also will require a comprehensive plan for dewatering the construction area.
- How the ends of the new dam configuration tie-in at the abutments may require special attention.

CONSIDERATIONS:



Option 2: Use Buttressing

Another way to improve stability of an earth embankment dam is to build a stabilizing fill buttress against the unstable slope (Figure 2.3.5). Adding buttress fill gives counteracting weight and added strength to the embankment to resist slope failure. A stability analysis performed by an engineer is needed to determine the best buttress shape.

When evaluating this option, keep these considerations in mind:

- A rockfill buttress also can be used for stabilizing a concrete or masonry dam.
- This option requires additional land downstream of the dam.
- An inclined chimney drain and downstream blanket drain can be added into the design by an engineer to handle seepage. (See Figure 2.3.17)
- If land downstream is not available, the same considerations apply for working upstream of the dam as discussed in Option 1: Reduce the Slope Angle.

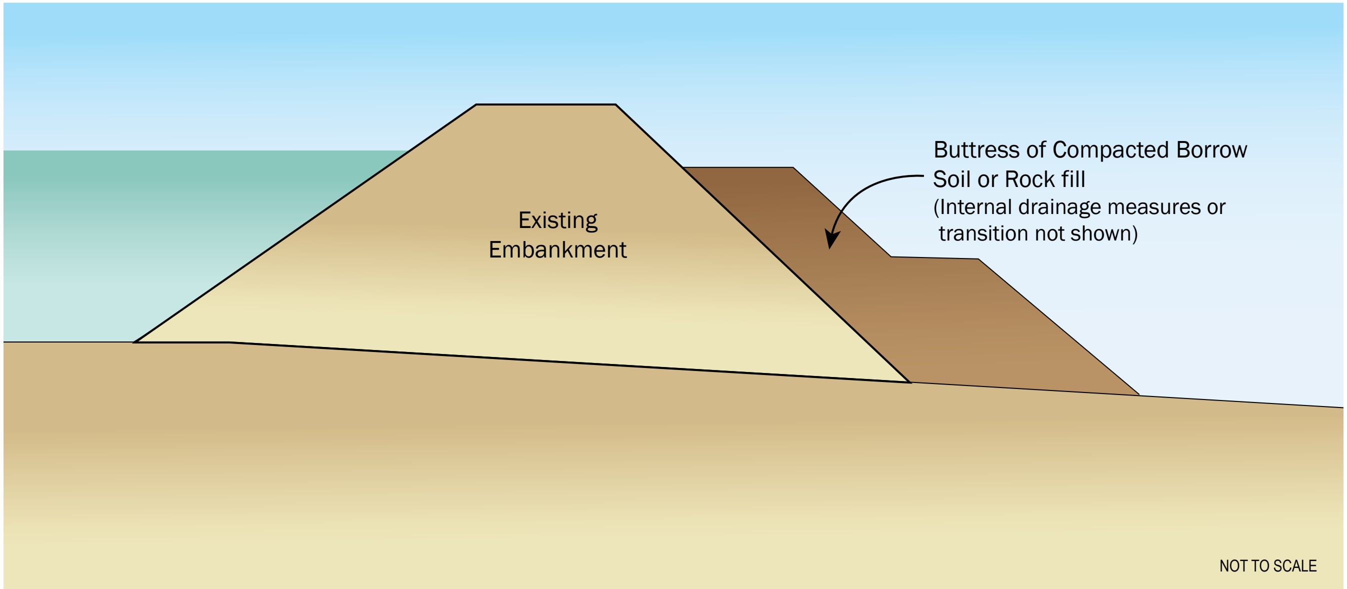
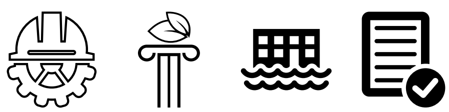


Figure 2.3.5. Buttressing can give additional stability to embankment dams.

CONSIDERATIONS:



Option 3: Use Anchoring

Concrete dams and concrete spillways are at risk for overturning or sliding if the force of the water they contain becomes great enough during or after a flood or hurricane. A common way to stabilize these structures is to use anchors installed into foundation rock. Vertical anchors work to resist overturning and also enhance sliding resistance. Inclined anchors help to resist sliding (Figure 2.3.6). Base the number, size, depth, and capacity of anchors on a stability analysis of the structure performed by an engineer following current practice and regulations.

When evaluating this option, keep these considerations in mind:

- Anchors may also be used to stabilize concrete foundations for risers and other elements.
- Masonry dams may have inside structures that make installing anchors through the dam itself unsuitable; keyed and anchored toe blocks are potential measures for stabilizing masonry dams.

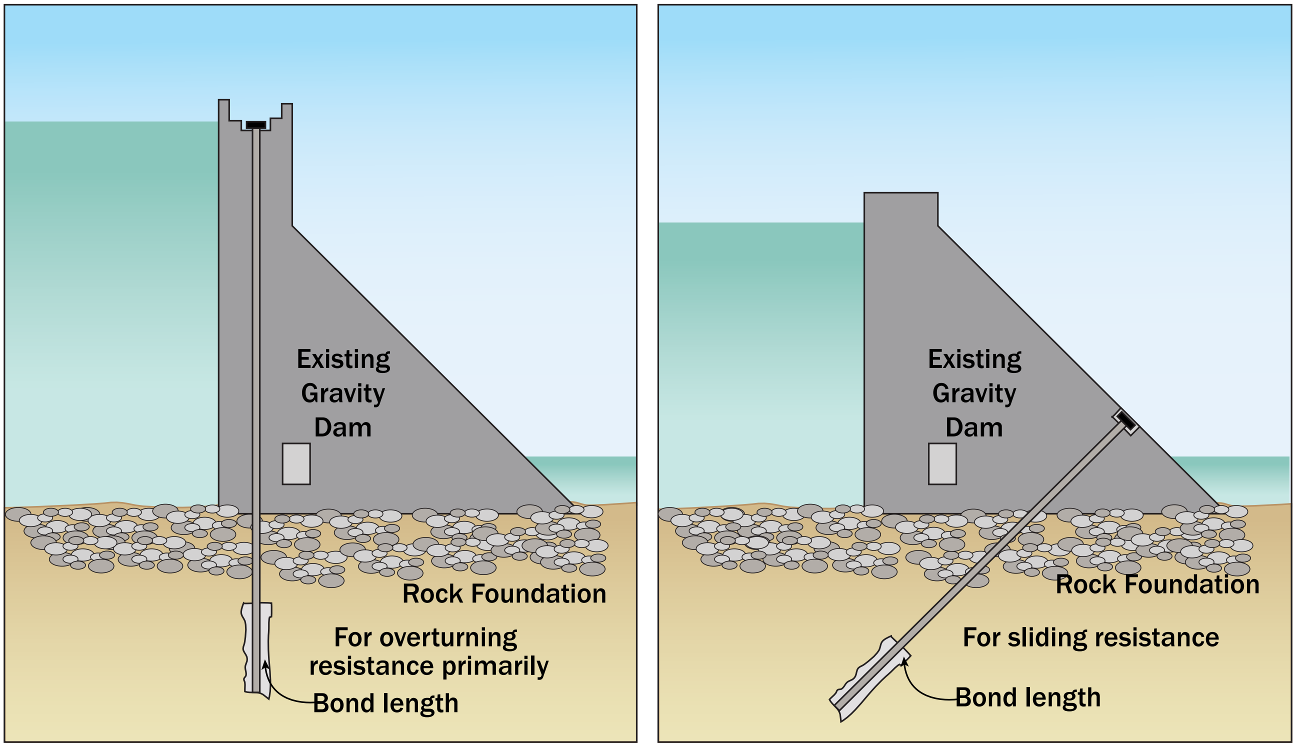
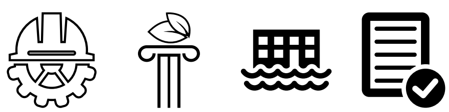


Figure 2.3.6. Anchoring can give resistance to overturning and sliding.

CONSIDERATIONS:



Mitigation Solution: Increase Spillway Capacity

A reservoir (also called an impoundment) is a basin behind a dam designed to store water for a hydropower system, water supply or other purposes. It must be able to store water and safely pass flood flows through a spillway to meet regulations based on the hazard potential classification of the dam.

Due to downstream development in flood zones, adjustments in hazard potential classification have occurred. These changes have left many impoundments without sufficient spillway size or flood storage volume to meet current safety standards.

Option 1: Expand Existing Spillway

One way to increase the size of an existing spillway is to widen it to increase its outflow volume (Figure 2.3.7). A hydrologic and hydraulic (H&H) analysis must be done by an engineer in accordance with current practice and regulations to determine the final design of the expanded spillway.

When evaluating this option, keep these considerations in mind:

- The auxiliary (or emergency) spillway also may be expanded.
- Spillway alteration may cause larger or more frequent releases of water, which could cause flooding in downstream areas, requiring careful planning and permitting.

CONSIDERATIONS:

Option 2: Add New Spillway

To meet the total additional capacity needed, it might be necessary to build a new spillway (Figure 2.3.7), in addition to expanding the existing spillway. An H&H analysis must be done by an engineer to determine the final design.

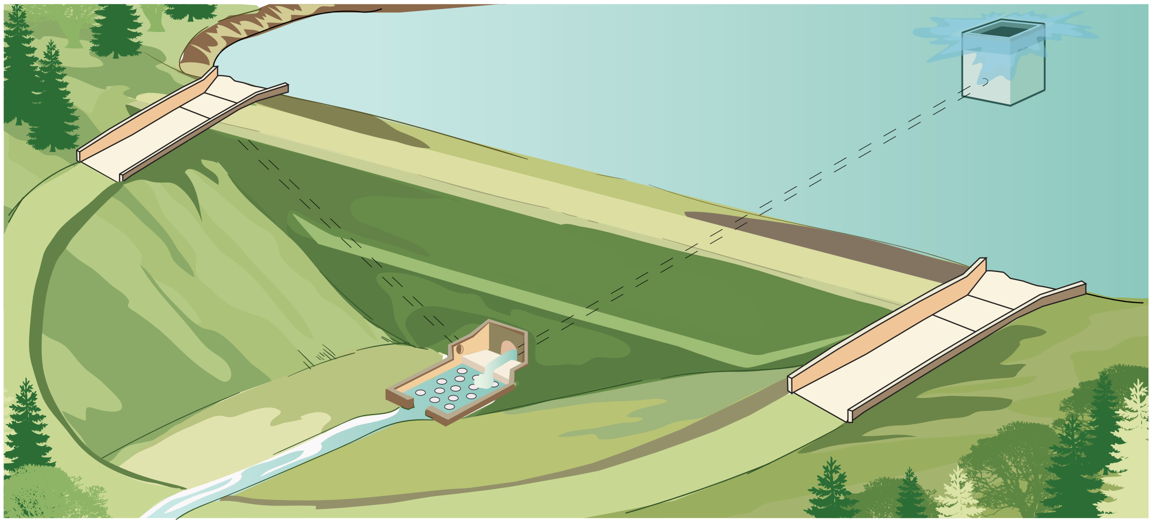
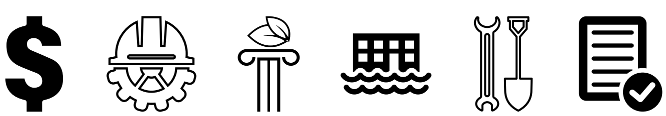


Figure 2.3.7. To increase spillway capacity, widen an existing spillway or build a second spillway.

When evaluating this option, keep these considerations in mind:

- Spillway alteration may cause larger or more frequent releases of water, which could cause flooding in downstream areas requiring careful planning and permitting.
- Expanding an existing auxiliary spillway or adding a new auxiliary spillway usually requires nearby land for development. If land is not available, potential alternatives for increasing spillway volume may include:
    - For impoundments with relatively small drainage areas, replace the existing main spillway with a much larger combined spillway system. Also consider adding the combined spillway while keeping the original main spillway if it is in good operating condition.
    - Build an auxiliary spillway using roller-compacted concrete (RCC), cable-stayed articulated concrete blocks (ACBs), or other suitable armor (see Option 1: Use Armoring, in the Mitigation Solution: Control Erosion and Retrofit for Overtopping Protection below in this Fact Sheet).

CONSIDERATIONS:



Mitigation Solution: Increase Temporary Storage Capacity

Some dams may be high enough to contain the flood pool but have little or no freeboard to give temporary storage capacity for larger than expected floods. Raising the dam height may be necessary to meet freeboard requirements.

Freeboard: An added margin of safety expressed in feet above a specific flood elevation.

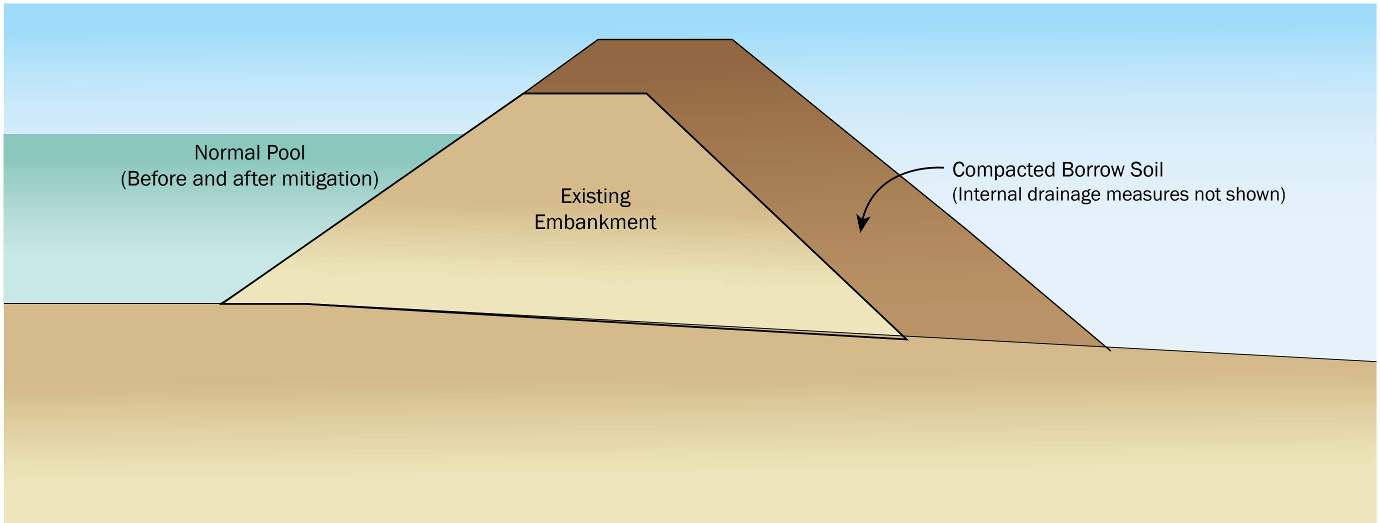
Option 1: Raise the Dam Height

Increase temporary flood storage capacity by adding freeboard to the height of the dam (Figure 2.3.8). Some dams may be high enough to contain the flood pool but have little or no freeboard to give temporary storage capacity for floods greater than expected.

Raise an earth embankment dam by expanding it higher in either the downstream direction or in the upstream direction. The dam raise must be engineered to include stable slopes, appropriate internal drainage measures, and external protective measures.

Note

Increasing freeboard to give overtopping protection by increasing temporary flood capacity is a mitigation technique. Increasing normal pool is not a mitigation technique because it raises dam risk by increasing the amount of water stored in the reservoir, thereby increasing the potential inundation area downstream.



Land Side Construction

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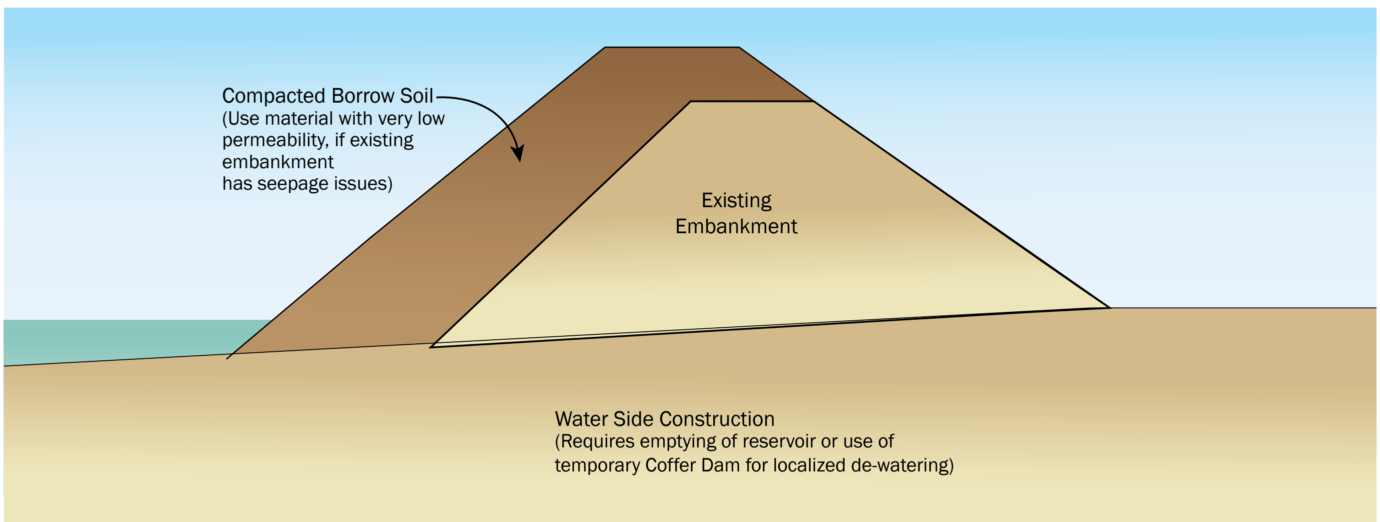


Water Side Construction

NOT TO SCALE

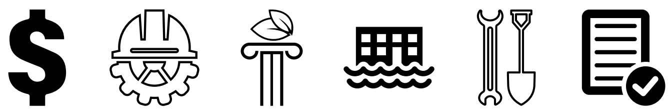
Figure 2.3.8. Raising the height of a dam can increase temporary flood storage capacity.

When evaluating this option, keep these considerations in mind:

- Raising the dam can increase the reservoir storage volume and result in larger flood areas upstream and downstream. Often, when the dam height is raised, the spillway(s) are also altered, which may result in larger releases and flooding in downstream areas. These projects must be designed and engineered carefully.
- If the dam raise embankment section is built using compacted borrow soil, place a filter drainage blanket between the existing embankment soil and new embankment soil on the downstream side.
- Building the outer part of the new embankment section with rockfill will allow a steeper slope (requiring less land downstream). A transition filter between the rockfill and the existing and new embankment soil would be needed.
- Add an inclined chimney drain and downstream blanket drain (Figure 2.3.17) to the design by an engineer to address seepage.

- Expanding downstream is more practical if land is available. If downstream land is not available, the new embankment can be built on the upstream side using the same considerations for working upstream of the dam as discussed earlier in this Fact Sheet.
- If the existing embankment shows signs of seepage on the downstream slope, the upstream embankment that is being raised should be built with compacted low-permeability soil or have an "impervious" blanket built along the upstream slope.
- Using parapet wall sections in combination with raising the dam embankment can lessen the required height of fill being placed.
- Raising the height of an embankment dam without changing the main body of the embankment may be feasible using mechanically stabilized earth (MSE) fill, RCC, or soil-cement.

CONSIDERATIONS:



Mitigation Solution: Control Surface Erosion

Embankment dams can be affected by erosion from wave run-up, overtopping and headcut. Erosion of an unprotected or poorly protected embankment by wave run-up could lead to a dam breach during a major flood (Figure 2.3.9). Overtopping can cause extreme erosion of an embankment dam, which can threaten total breach of the dam and release of the reservoir to the downstream area (Figure 2.3.10). Another serious form of erosion is headcut erosion caused by a major flood. Progressive headcut erosion could lead to release of a major portion of the reservoir to the downstream area, if the headcut advances back to the reservoir (Figure 2.3.11). Even for a dam that has enough freeboard and a wide crest, erosion could become progressively worse and lead to a costlier repair if left uncorrected.

Terminology – Causes of Erosion

Wave run-up: Vertical height above the still water level to which water from a specific wave will run up the face of a structure or embankment

Overtopping: When the reservoir water level exceeds the height of the dam crest and water spills over the top of the dam

Headcut: An erosion process where flow of sufficient energy creates a flaw in the ground surface. Flow then concentrates at the flaw and erosion initiates an abrupt drop in the ground surface.

Figure 2.3.9. Wave action can erode the upstream slope of a dam. (Source: USFWS, 2008)


Figure 2.3.10. Initial embankment overtopping can lead to a complete overflow. (Source: USFWS, 2008)

Figure 2.3.11. Headcut erosion could lead to an accidental release from the impoundment. (Source: NRCS, 2017)

Option 1: Use Armoring

Potential retrofits for erosion control include various types of armoring as described in the sections below.

RIPRAP BLANKETS

Riprap blankets are commonly used to repair upstream embankments damaged by waves (Figure 2.3.12 and Figure 2.3.13). Riprap also is commonly used to repair eroded ditches, dam toes, outlet basins and channels. Riprap blankets must be designed by an engineer to choose the appropriate materials for compatibility with the embankment material to resist wave action.

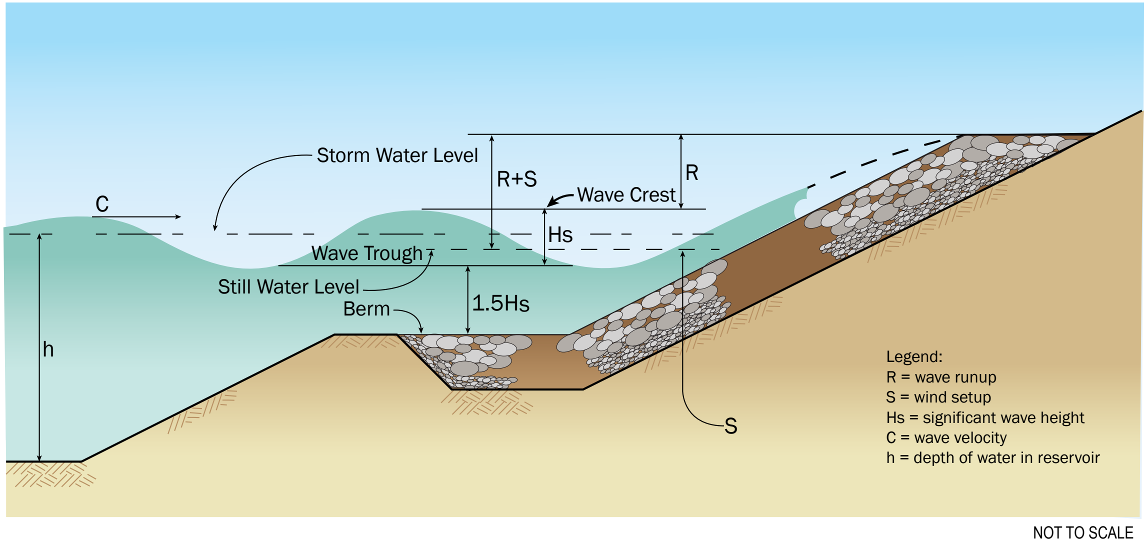


Figure 2.3.12. Riprap layouts can be designed to protect against wave action.(Source: NRCS, 1983)

Figure 2.3.13. Riprap blankets can protect against wave action. (Source: USFWS, 2008)

CONCRETE SLABS AND SOIL CEMENT

To protect against wave erosion, consider reinforced concrete slabs and soil cement. These armoring methods may require more foundation preparation than for riprap in repairing a wave-eroded embankment.

TURF REINFORCEMENT MAT

Turf reinforcement mats work with plant root systems to protect earthen slopes against erosion. They can be designed to reinforce spillways or other earthen areas where calculated flow velocities are within design standards and comply with manufacturer's recommendations.

ARTICULATED CONCRETE BLOCKS AND ROLLER-COMPACTED CONCRETE

Articulated concrete blocks (ACBs) and roller-compacted concrete (RCC) are commonly used to protect embankments from erosion associated with overtopping, particularly when options for increasing spillway capacity are limited or non-existent (Figure 2.3.14). Overtopping protection often is designed to serve as an auxiliary spillway. Tapered wedge blocks also have been used in overtopping retrofits.

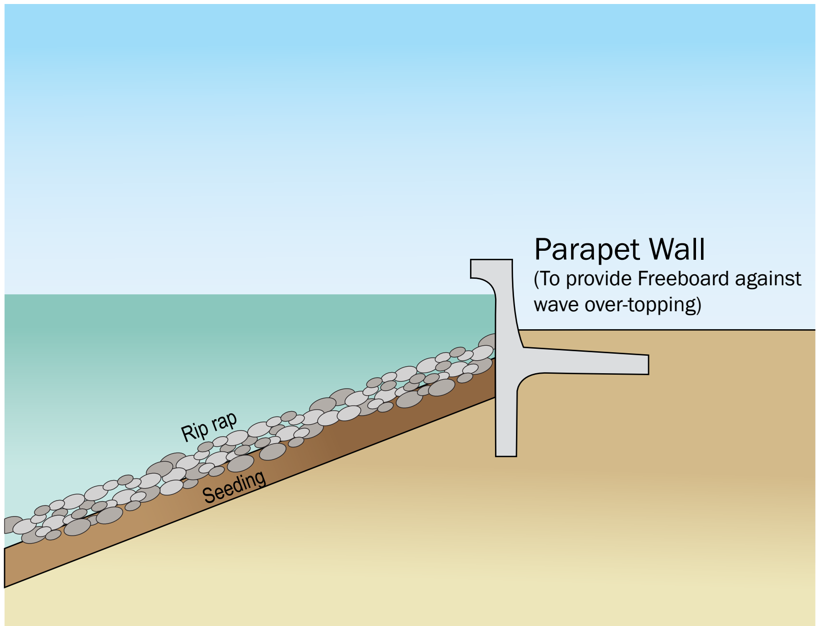
Figure 2.3.14. ACBs (left) and RCC (right) can protect spillways from overtopping erosion.

ACBs, RCC and tapered wedge blocks, as well as gabions, riprap and reinforced concrete paving all are potential armoring options for retrofitting existing unarmored auxiliary spillways. The material choice will depend in part on design and constraints.

CONSIDERATIONS:

Option 2: Build a Parapet Wall

A common method to protect against erosion from wave run-up is to install a reinforced concrete parapet wall (Figure 2.3.15). Parapet walls must be engineered for site-specific conditions.



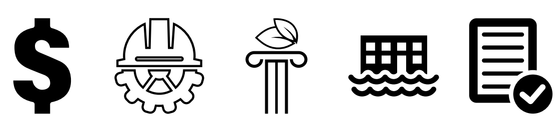
NOT TO SCALE

Figure 2.3.15. A parapet wall can give additional freeboard to protect against wave overtopping. (Source: USACE, 2004)

When evaluating this option, keep these considerations in mind:

- Parapet walls are most effective when the upstream slope has an armored facing, such as concrete slab or asphalt, that provides resistance to wave action.
- Design the wall with a curved face to deflect waves more effectively and increase the height of the wall.
- Parapet walls also may be installed on concrete dams (non-overflow sections) to help minimize the required elevation of the crest when raising the dam height.
- Galvanized steel also may be used to build a parapet wall, or the wall can include sheet piles or corrugated steel panels spanning between posts. Steel may be better suited to projects in dry climates or where the soils are not highly corrosive.

CONSIDERATIONS:



Option 3: Build a Cutoff Wall to Address Headcutting

Improve existing unarmored auxiliary spillways with erodible foundations by installing one or more cutoff walls to block the advance of headcut erosion (Figure 2.3.16).

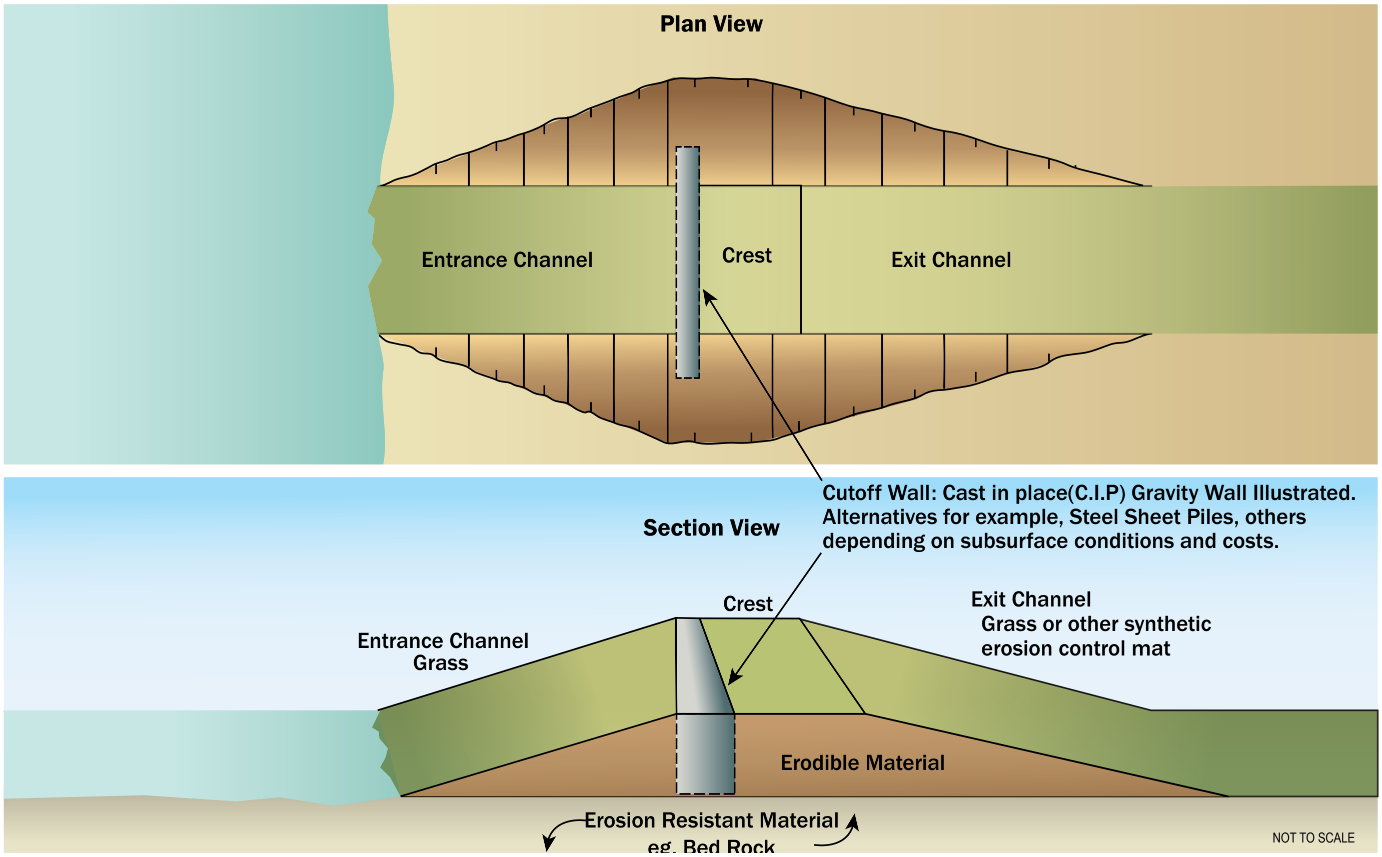
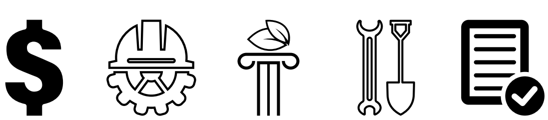


Figure 2.3.16. Cutoff walls can improve the stability of some unarmored auxiliary spillways.

When evaluating this option, keep these considerations in mind:

- This type of retrofit is best for sites with a shallow depth to reach non-erodible material (e.g., bedrock) and infrequent use of the auxiliary spillway.
- Cutoff walls generally are not used at sites where erodible soils extend to great depth.
  - A potential exception occurs if it is determined that flows through the auxiliary spillway have short durations.
  - Engineering analysis should be completed to show that the headcut depth does not extend below the cutoff wall.

CONSIDERATIONS:



Mitigation Solution: Reduce Seepage and Internal Erosion

Option 1: Install a Blanket Drain

Install seepage blanket drains to increase seepage flow paths and reduce the risk of seepage-related piping by retaining embankment soil and conveying the seepage water to a designed exit (Figure 2.3.17).

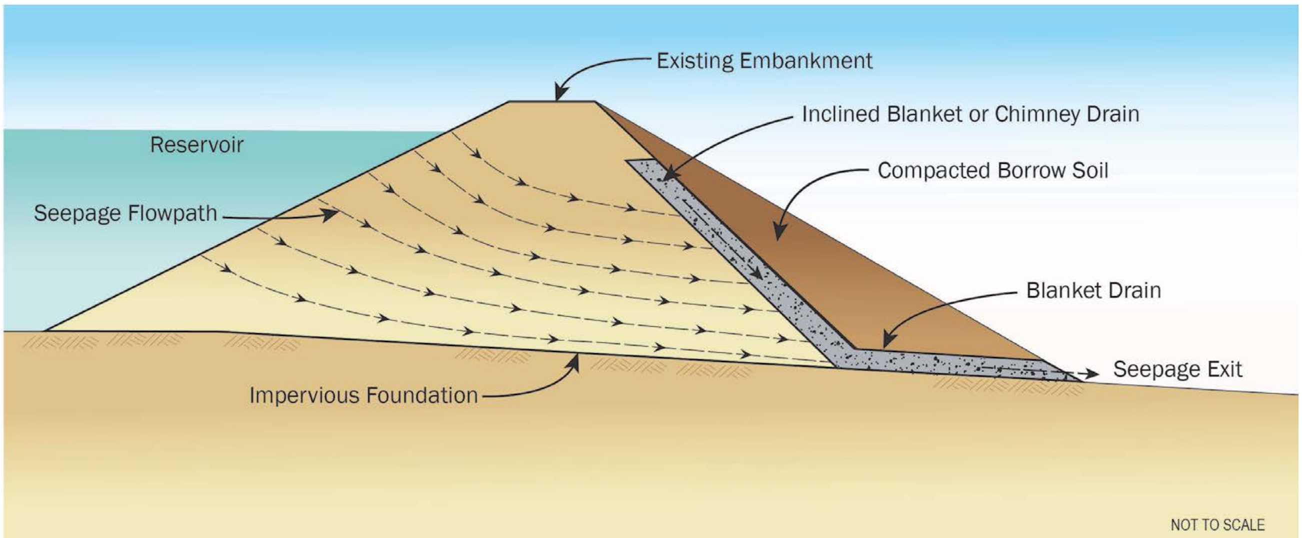
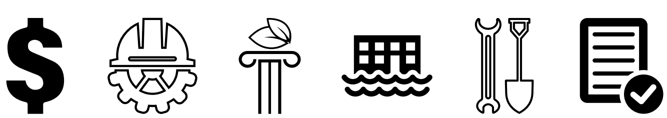


Figure 2.3.17. Blanket drains increase seepage flow paths and reduce the risk of seepage-related piping.

When evaluating this option, keep these considerations in mind:

- Geotechnical analysis of dam materials is required. Base selection of filter materials on compatibility with dam materials.
  - Specific gradation material may be hard to manufacture or find at regular quarry.
  - Use of materials that are not compatible with embankment soils can lead to migration of soils and increased risk of piping.
- This mitigation solution can be combined with reducing the slope angle to increase dam stability.

CONSIDERATIONS:



Option 2: Install a Filter Diaphragm

A filter diaphragm is a designed zone of filter material (usually well-graded, clean sand) built around a conduit to prevent seepage, erosion, and piping through cracks that may occur in compacted fill near conduits or at the interface between the conduit and the surrounding fill. The filter materials are designed to retain embankment soils while allowing seepage water to pass (Figure 2.3.18). Filter diaphragms may be designed in conjunction with internal drainage systems like blanket drains, chimney drains, or transition zones to convey the seepage.

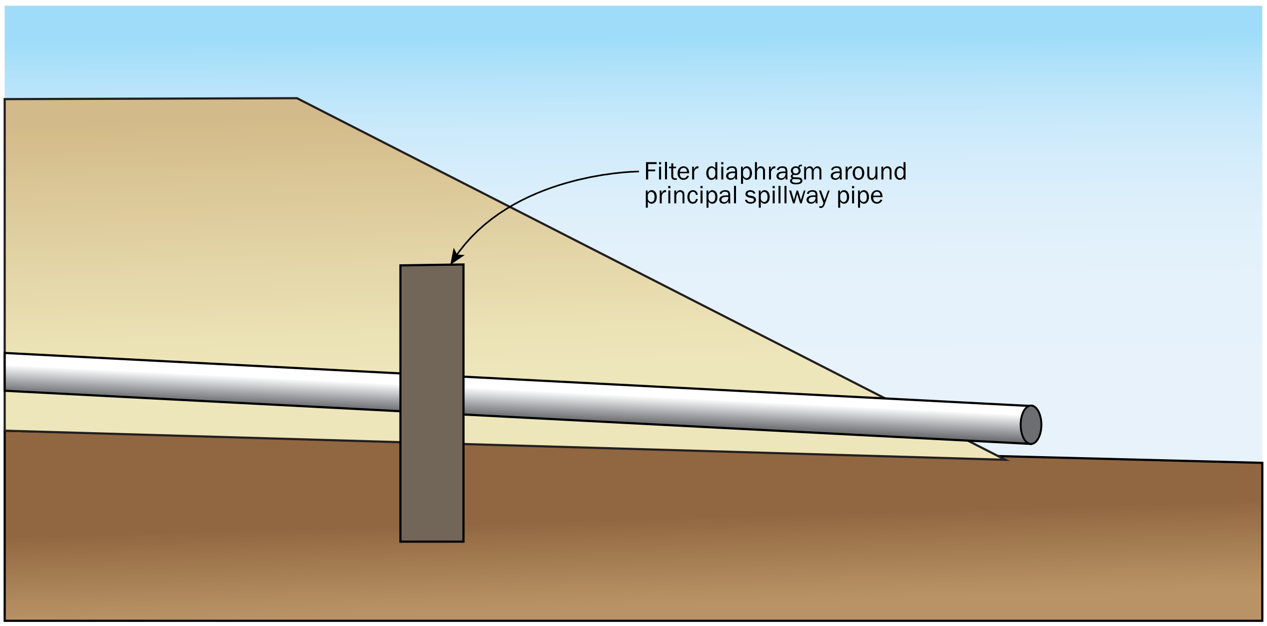
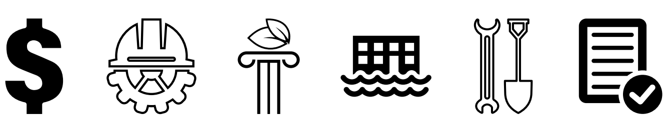


Figure 2.3.18. Filter diaphragms can prevent seepage around conduits.

When evaluating this option, keep these considerations in mind:

- Geotechnical analysis of dam materials is required. Base selection of filter materials on compatibility with dam materials.
    - Specific gradation material may be hard to manufacture or find at regular quarry.
    - Use of materials that are not compatible with embankment soils can lead to migration of soils and increased risk of piping.
- This mitigation solution can be combined with other drainage systems to convey seepage water to a designed exit.

CONSIDERATIONS:



Option 3: Install a Reverse Filter

Reverse filters are designed zones of filter material used to address sinkholes (Figure 2.3.19). The sinkhole throat is plugged with large pieces of concrete rubble or riprap to slow the migration of material into the sinkhole. Layers of finer materials (gravel then sand) are then placed to stop the migration of embankment materials into the voids between the rubble or gravel pieces. Cap the reverse filter with a filter fabric and fine material to bring the area back to desired grade and limit the influence of surface drainage on the area.

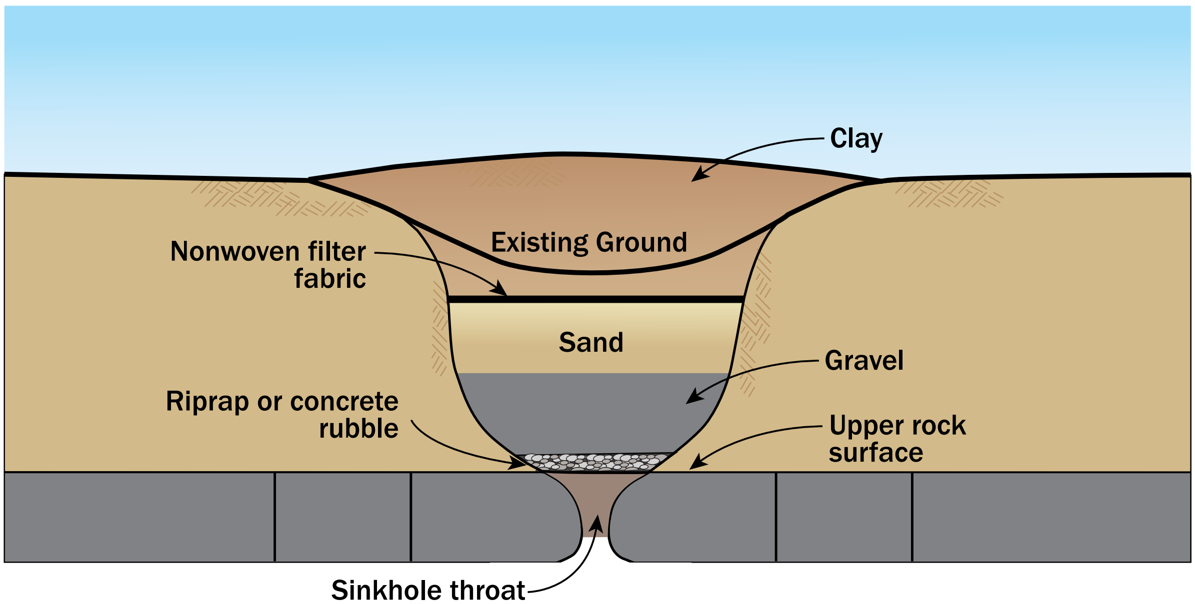
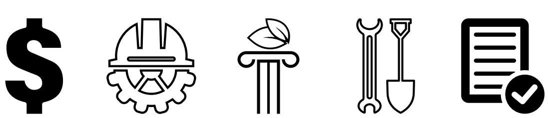


Figure 2.3.19. Reverse filters can be used to address sinkholes.

When evaluating this option, keep these considerations in mind:

- Geotechnical analysis of dam materials is highly recommended. Base selection of filter materials on compatibility with dam materials.
  - Specific gradation material may be hard to manufacture or find at regular quarry.
  - Use of materials that are not compatible with embankment soils can lead to migration of soils and increased risk of piping.
- This mitigation solution can be used as an emergency remedial action. Pay close attention to changing conditions to act in a timely manner. Sinkholes, seepage and piping can evolve quickly, so constant surveillance from a safe vantage point is recommended.

CONSIDERATIONS:



Option 4: Install a Seepage Cutoff Wall

Build seepage cutoff walls to control seepage through an earthen dam. There are various methods for building cutoff walls including:

- Earth-backfilled slurry trench cutoff walls
- Cement-bentonite slurry trench cutoff walls
- Soil-cement-bentonite cutoff walls
- Concrete cutoff walls
- Deep soil mixing cutoff walls
- Secant pile cutoff walls
- Sheet pile cutoff walls
- Jet grouted cutoff walls

When evaluating this option, keep these considerations in mind:

- The reservoir may need to be lowered to facilitate building a cutoff wall.
- Geotechnical analysis of dam foundation materials is required. The type of foundation materials may limit the types of cutoff walls that can be built.
- The required depth of the cutoff wall may limit the type of cutoff wall selected due to limitations in construction equipment reach and depth of excavation capability.
- Depending on the type of cutoff wall, it may be an expensive mitigation measure.

DEEP SOIL MIXING

Deep soil mixing is a method where trenching machines are used to excavate materials along a line, mix the excavated materials with cement or bentonite, and the treated materials are returned to the trench to form a seepage cutoff wall (Figure 2.3.20).

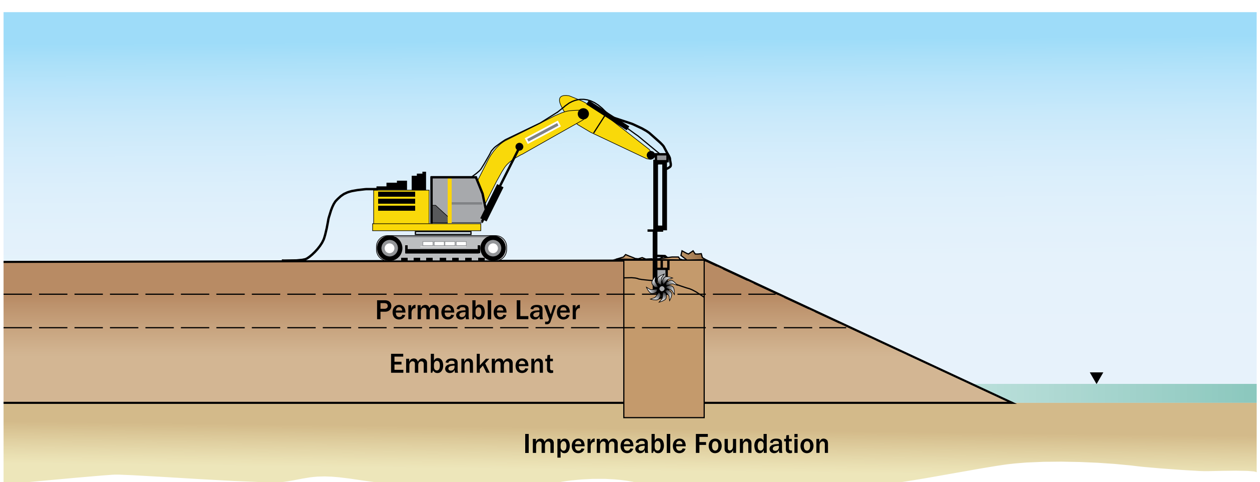


Figure 2.3.20. Seepage cutoff walls can be achieved through deep soil mixing.

SECANT PILE WALL

Secant pile walls are built in a similar way to deep soil mixing (Figure 2.3.21). Instead of a trenched wall, large boreholes are drilled, the excavated materials are mixed with specialized cement or bentonite, and then returned to the borehole to form a reinforced column of soil. Space the boreholes in such a way that the columns overlap and create a reinforced soil wall to address seepage.

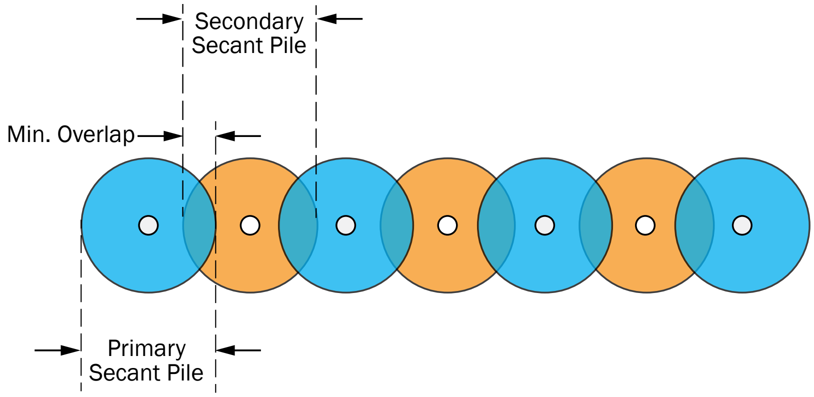
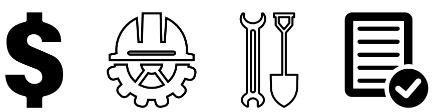


Figure 2.3.21. Plan view of a secant pile wall.

Primary secant piles are installed and given time to cure. The secondary secant piles are installed after the primary secant piles have cured to form a continuous wall.

CONSIDERATIONS:



Mitigation Solution: Address Foundation Issues

Option 1: Install a Grout Curtain

Grout curtains are built by forcing grout under pressure into lines of boreholes that extend to the rock foundation of the dam. The borehole lines are drilled at angles that overlap, creating a curtain (Figure 2.3.22). The grout is pressurized when it is put into the borehole to fill cracks in the foundation of a dam and prevent seepage.

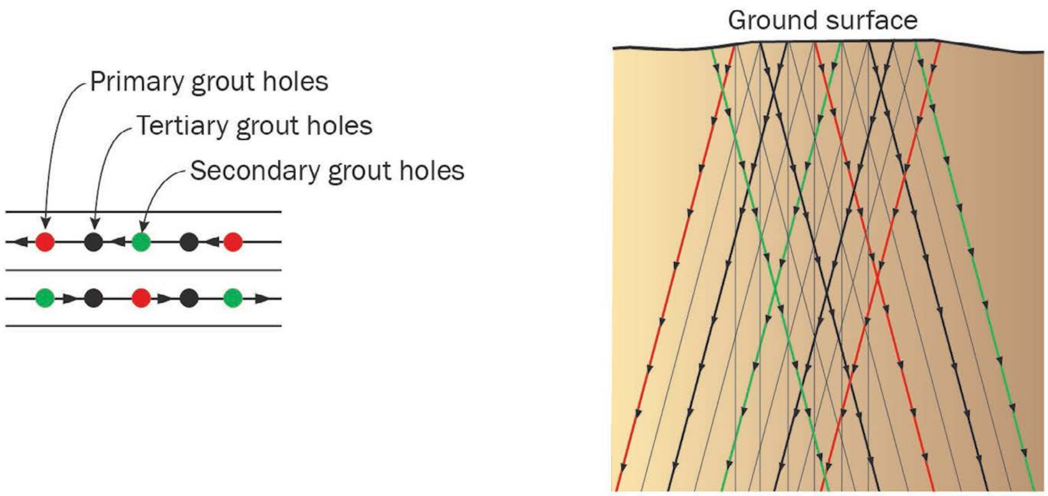
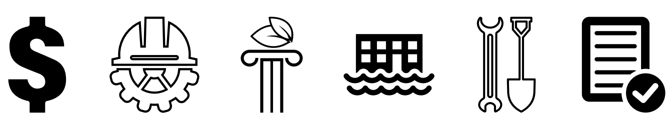


Figure 2.3.22. Plan and profile of a grout curtain design.

When evaluating this option, keep these considerations in mind:

- Geotechnical analysis of dam foundation materials is required.
- Grout pressure must be high enough to fill foundation cracks but not high enough to move embankment materials
- It may be difficult to maintain pressure in the grout boreholes if the seepage path is severe. Installing phased lines of grout in different directions may help address this issue.

CONSIDERATIONS:



Option 2: Install a Foundation Cutoff Wall

Foundation cutoff walls are seepage cutoff walls that are constructed to control seepage through a dam foundation (Figure 2.3.23). The same methods are used to construct foundation cutoff walls:

- Earth-backfilled slurry trench cutoff walls
- Cement-bentonite slurry trench cutoff walls
- Soil-cement-bentonite cutoff walls
- Concrete cutoff walls
- Deep soil mixing cutoff walls
- Secant pile cutoff walls
- Sheet pile cutoff walls
- Jet grouted cutoff walls

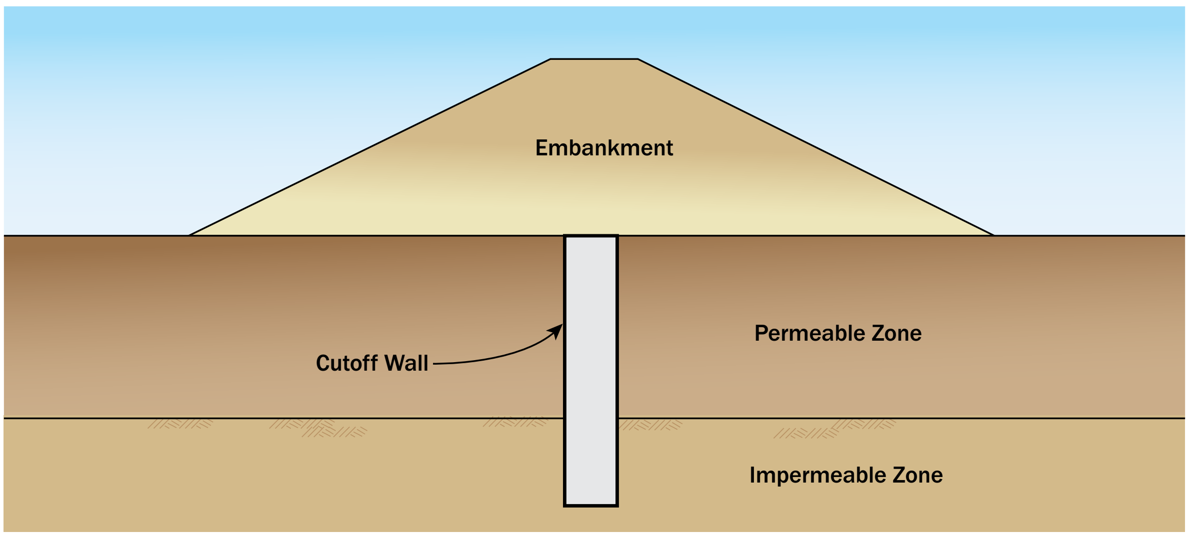
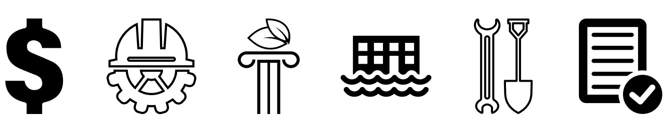


Figure 2.3.23. Foundation cutoff walls can help control seepage through a dam foundation.

When evaluating this option, keep these considerations in mind:

- The reservoir may need to be lowered to facilitate construction of a cutoff wall.
- Geotechnical analysis of dam foundation materials is required. Extent of permeable foundation zones and types of in-situ materials may limit the types of cutoff walls that can be constructed.
- The required depth of the cutoff wall may limit the type of cutoff wall selected due to limitations in construction equipment reach and depth of excavation capability.
- Depending on the type of cutoff wall, it may be an expensive mitigation measure.

CONSIDERATIONS:



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