RECLAMATION

Managing Water in the West

Canal Operation and Maintenance:

Embankments

U.S. Department of the Interior
Bureau of Reclamation
Office of Policy
Technical Service Center
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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Disclaimer

Reclamation developed this manual to provide basic guidance to help canal operators promote safe and effective operations and maintenance for canal systems. This information complements—and does not replace—experience and sound judgment. This is general information useful for typical canal systems. As each canal system has unique designs and features, these general guidelines cannot substitute for facility or operating-specific guidance and specifications. Every operating entity is different, and this advice and strategies may not be suitable for all situations.

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
ATV	all terrain vehicle
cfs	cubic foot per second
EAP	Emergency Action Plan
ECM	Erosion control matting
EMP	Emergency Management Plan
FEMA	Federal Emergency Management Agency
gpm	gallon per minute
H:V	horizontal:vertical
IR	infrared
PI	plasticity index
psi	pound per square inch
Reclamation	Bureau of Reclamation
SOP	Standing Operating Procedures
TSC	Technical Service Center
USACE	U.S. Army Corps of Engineers
UV	ultraviolet

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1. Purpose and Scope of Guidance

This manual has been prepared to help operating entities better understand how embankment distress can lead to a canal failure (Figure 1), types of embankment distress commonly encountered, how an inspection and monitoring program can reduce the likelihood of failure, methods that may be used to repair an embankment, and best practices for responding to a developing failure. Types of embankment distress addressed by this manual include:

- Seepage and internal erosion
- Slope instability
- Surface erosion

Figure 1. Example of a recent canal failure.

Bureau of Reclamation (Reclamation) staff are available to provide advice and technical support on Reclamation-owned canals. Contact Reclamation and consider additional engineering support before making modifications to the canal. If you determine work outlined in this manual requires more expertise than your staff can provide, please contact Reclamation for technical support at: www.usbr.gov/main/offices.html.

Damage to embankments may also be caused by burrowing animals and vegetation (i.e., tree root systems). These issues are discussed separately in Reclamation's Canal Operation and Maintenance manuals for burrowing animals (Reclamation 2017 [Animals] and vegetation control (Reclamation 2017 [Vegetation]).

Where canal lining is found to be in poor condition but seepage losses or safety of the embankment is not the primary concern, see guidance provided in Reclamation's concrete repair manual for condition assessment and repair recommendations: www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Guide2ConcreteRepair2015_Final.pdf. Where seepage may not always be a primary concern, concrete repairs can still improve operations and canal capacities. Reclamation's Canal Operation and Maintenance: Concrete manual has more information on maintaining concrete lining and structures (Reclamation 2017 [Concrete]).

2. Seepage and Internal Erosion

Canal systems are used to convey water from natural water courses or from storage impoundments to delivery points, sometimes hundreds of miles away. In addition to conveying irrigation water, a canal may provide water for municipal, industrial, and outdoor recreational users. Along the canal's course, seepage losses inevitably occur. Seepage which travels downwards into the foundation does not threaten the integrity of the canal embankment, but this can affect the canal's efficiency and ability to make downstream deliveries. Seepage which travels horizontally through a flaw in the embankment or shallow foundation has the potential to lead to a canal failure if the right conditions exist or if the seepage is undetected and/or is allowed to worsen over time.

2.1. Conditions Often Attributed to Seepage and Internal Erosion

Conditions can vary greatly along the length of a canal (Figure 2). The canal may traverse various geologic settings, transition from cut to fill construction depending on the surrounding terrain, and cross numerous natural drainages. Seepage and seepage related failures are most often attributed to conditions:

- Where the canal crosses natural drainages where coarser alluvial soils might exist
- Where the canal was constructed through geologic deposits that are more susceptible to erosion (i.e., granular materials)
- Where soluble materials exist in the foundation (e.g., caliche)
- Where the canal is elevated above the surrounding terrain and/or the embankment is narrow
- Along construction flaws such as segregated or poorly compacted fill lifts
- Where differential settlements and cracking may have occurred
- Along flaws created by burrowing animals or decaying tree root systems

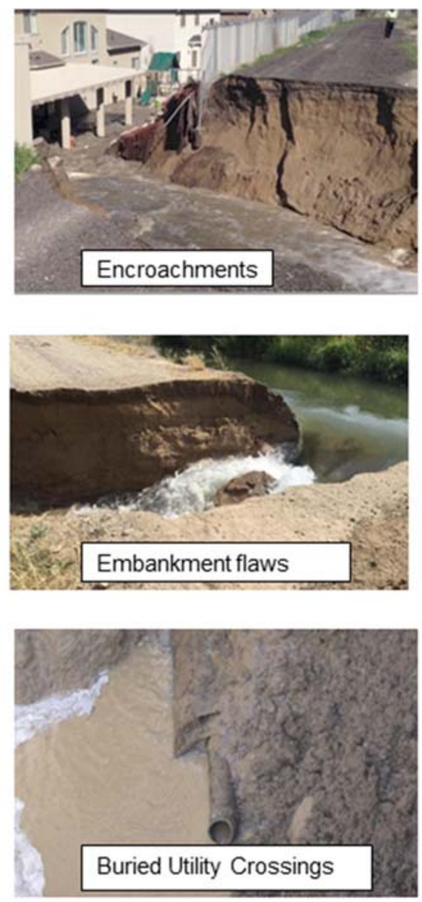

Figure 2. Examples of embankment issues.

- Along embankment penetrations such as laterals, turnouts and buried utility crossings
- Where canal lining has failed or is in disrepair
- Where unauthorized embankment modifications have been made (e.g., excavations at the embankment toe)

Most embankment and foundation flaws are noted during the first few years of operation or following an extended shutdown. These flaws and associated seeps often require placing additional lining and/or modifying embankments to maintain reliable deliveries. Once the canal has been operating for a number of years, a change in condition is required for seepage to worsen to an extent that might lead to a failure. Changes in condition might include: higher than normal canal flows/water level, hydrologic or seismic events, cleaning activities, inadequate maintenance practices, construction, or other activities by the surrounding public.

2.2. Impacts to Canal Efficiency and Deliveries

This manual is intended to discuss seepage in relation to the potential for a canal failure. However, seepage losses are also an important factor on water availability and allocations. Seepage losses can represent a significant percentage of the water diverted at the canal headworks. Seepage losses may occur at a relatively uniform rate along the length of the canal, or at higher rates at discrete locations. Unlined canals often have the highest seepage losses. Should the seepage losses be large enough, deliveries may not be made to the end users.

Measures most often used to improve canal efficiency include installing canal lining or using pipelines in high seepage loss areas. These options can be costly. Financial support and grant programs may be available, so contact your local Reclamation office.

2.3. How Seepage Can Lead to a Canal Failure

Should concentrated seepage develop, go undetected, or be ignored it can lead to an internal erosion failure. Internal erosion failures are characterized by a series of events including initiation of erosion, continuation, progression, and ultimately failure. Internal erosion most often leads to a canal failure when the problem is neither observed nor detected, or when intervention is late or unsuccessful. Eventually, the canal fails by gross enlargement of the void which leads to a collapse of the embankment and uncontrolled release of the canal water.

Initiation of erosion often occurs by one of four ways: backwards erosion piping, internal migration, scour, and suffusion/suffosion[1] (Federal Emergency Management Agency [FEMA] 2015). These initiation mechanisms may occur alone or together during the progression of the internal erosion failure mode.

The initiation of erosion depends on the embankment geometry, foundation conditions, location of the internal erosion, and materials used for construction. Several physical properties of the embankment and foundation soils, such as gradation (particle size and uniformity), fines content, plasticity, density, and mineralogy affect "initiation." In general, soils with plasticity index greater than 7 or soils placed against a rigid structure or foundation unit, are most likely to initiate by the scour mechanism. Scour is the process of concentrated seepage along a flaw detaching soil particles and carrying them to a downstream exit. Granular or low plasticity to non-plastic soils are more likely to initiate and progress by backwards erosion piping, internal migration or suffusion/suffosion leading to formation of large voids within the embankment core.

For internal erosion to initiate and continue, all three of these conditions must be present:

- A source of water that develops localized seepage with enough force to lift a soil particle from its resting place
- Enough flow to carry particles in suspension or in bed load along an unobstructed path beyond the point where the soil particle has been removed from its resting place
- An unfiltered exit through which soil particles can be removed by seepage

An internal erosion failure progresses by developing and enlarging the erosion pathway through the embankment or foundation (Figure 3 is an example of an internal erosion process). This process will vary depending on the embankment geometry, foundation conditions, location of the internal erosion, and materials used for construction. Several physical properties of the embankment and foundation soils affect the "progression phase," including gradation (particle size and uniformity), fines content, plasticity, density, mineralogy, and the presence of a canal lining.

For internal erosion to progress:

- The soils being eroded, or the material immediately above the soils being eroded, must be capable of supporting a "roof" or sidewalls

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[1] Suffusion and suffosion are forms of internal erosion. Suffusion removes finer particles and usually does not change the volume of the soil, but suffosion also removes medium size particles and does decrease the volume of the soil.

- The flow along the erosion path has to be sufficient to maintain or increase the erosion rate

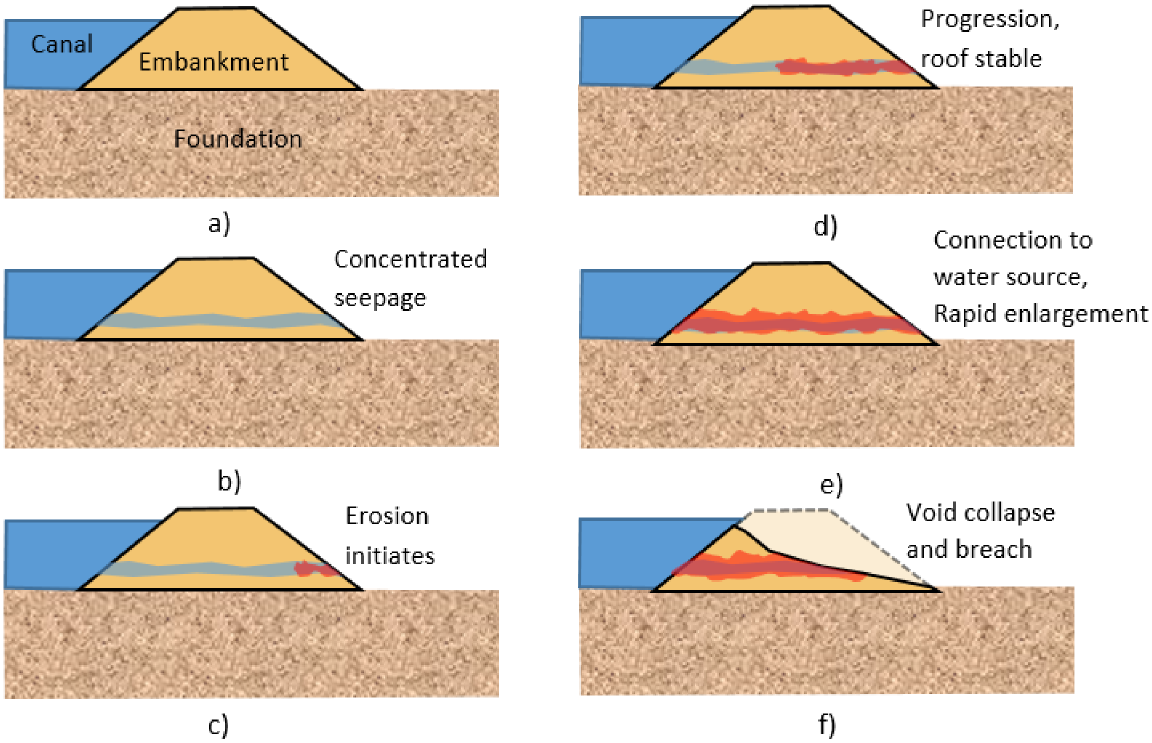

Figure 3. Example of a canal failure by backwards erosion piping (BEP).

Seepage itself is not indicative of an impending failure. Seeps characterized by wet ground or daylighting over a large area are unlikely to lead to an internal erosion failure. Seeps that exit within a localized area, appear to be discolored and carrying sediment, or express themselves as sand boils are of most concern and should be addressed immediately.

Canal lining does not preclude the possibility of a canal failure, but can slow the progression by limiting the seepage flow.

2.4. Seepage through the Foundation

If the canal's foundation is made up of soil, internal erosion through the foundation may occur by any of the mechanisms previously discussed. The most common mechanism is backward erosion that could be initiated by high exit gradients or blowout that is often revealed by sand boils.

Blowout could occur if a confining clay layer overlays a granular/permeable deposit that might be exposed in the base of the canal prism. For large canals with a soil foundation, Chapter 4 of the Best Practices for Dam and Levee Risk Analysis (Reclamation and the U.S. Army Corps of Engineers [USACE] 2015) should be reviewed to evaluate the potential for foundation blowout.

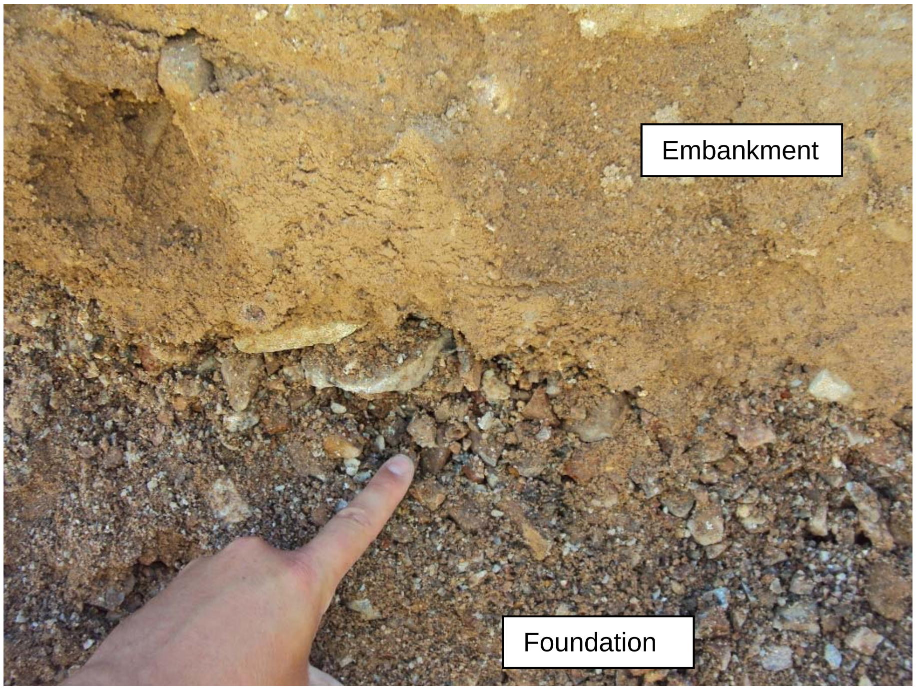

Figure 4. Embankment foundation contact.

Where granular-permeable foundation materials exist beneath a canal embankment, sand boils may develop where the seepage exits the surface (Figure 4). Sand boils may express themselves in three ways (Figure 5):

- Soil particles "dance" where the seepage exits but no material is being removed from the foundation

- A small amount of soil is initially eroded to form a sand cone/boil but the removal of soil from the foundation stops once the sand cone reaches a certain height

- The sand cone/boil forms rapidly and finer sediments from the foundation continue to be eroded as a void progresses towards the water source

Figure 5. Examples of dancing soil particles and a sand cone.

Figure 6 shows an example of how a sand boil forms and can lead to a canal failure. Emergency response measures to address sand boils are discussed in Section 5. *Emergency Preparedness, Intervention, and Communication.*

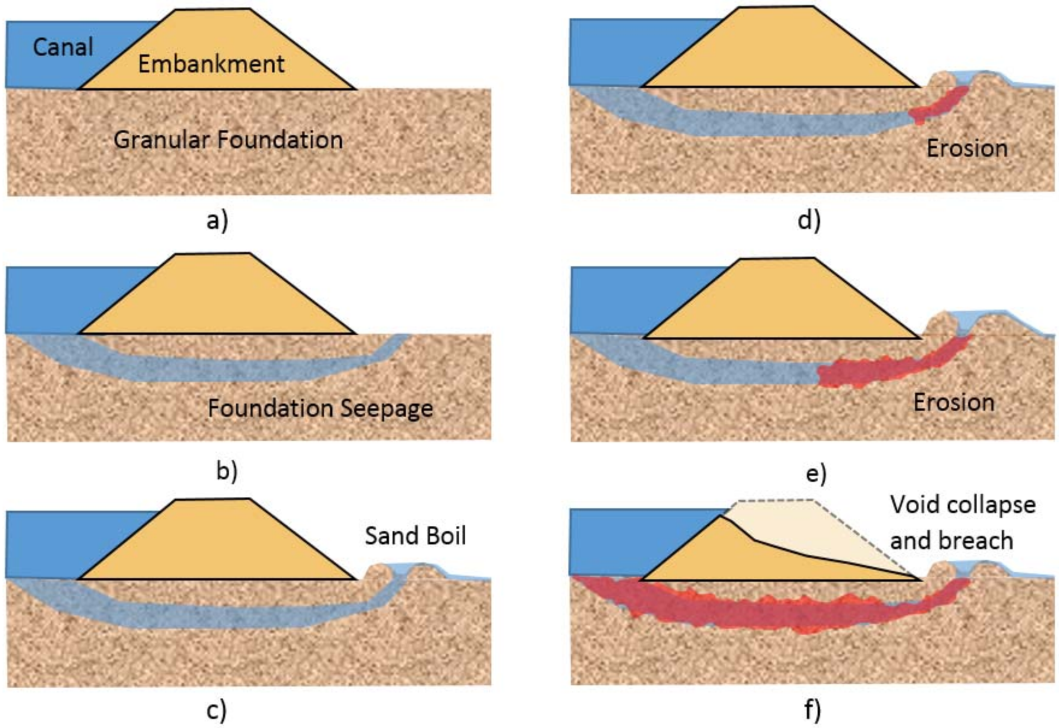

Figure 6. Sand boil progression to a canal failure.

2.5. Detection, Monitoring and Investigations

2.5.1. Detection

Seepage exiting the surface may be characterized as simply wet ground or cumulating with flows ranging from tens or hundreds of gallons per minute (gpm) to multiple cubic feet per second (cfs). Vegetation is a useful telltale sign of seepage because it establishes quickly where seepage exits the ground surface, even when surface flow may not be visible. If vegetation appears in a dry climate where vegetation is uncommon, it is an indication that seepage exists. Aerial infrared (IR) surveys are also useful to detect seepage when there are no surface flows or the seepage is traveling just below the ground surface. Soil resistivity profiles have also been used to locate concentrated seeps, but with limited success.

Canal seepage generally exits at or just beyond the toe of the embankment slope and is often attributed to a flaw at the embankment/foundation contact or pervious materials in the shallow foundation. When seepage exiting near the toe of the embankment is characterized by wet ground or small flow rates (only a few gpm), these seeps may just require regular monitoring. If the seepage is exiting from a concentrated location at a high rate (tens of gpm) or if there is evidence of material transport, then more frequent monitoring should be initiated and plans to make repairs should be developed.

In some instances, seepage may travel horizontally through shallow foundation materials and exit the ground surface hundreds of yards from the canal. This type of seepage is not a threat to canal safety, but can negatively affect the canal's efficiency and may require mitigation. Development or construction activities downslope from the canal can expose these shallow seepage paths, at which point they may need to addressed or more closely monitored.

Seepage that begins to exit from the embankment slope likely indicates a newly developed flaw and is cause for concern. If seepage from the embankment slope develops, then more frequent monitoring should be initiated and plans to make repairs should be developed.

2.5.2. Documentation and Monitoring

Once a seep has been identified it should be monitored regularly for any changes (- Figure 9). A database of the existing seeps should be developed and include:

- Dated photographs
- Drawings or sketches showing the seepage locations/limits
- Seepage rates for various canal flow conditions
- Surface markings for future canal operators

Canal operators should regularly visit each of the seeps in the database and record their observations in a standardized inspection checklist. Any changes should be highlighted and investigated further.

Figure 7. Example of a seepage area showing monitoring efforts and how the limits of a wetted seepage area have varied over time.

Figure 8. Example of initial measures used to collect and measure seepage flows.

Figure 9. Example of a ring dike constructed around a sand boil to reduce the exit gradient and measure the seepage flow.

2.5.3. Investigations

In instances where new seepage develops or is changing over time, an investigation should be conducted to better understand the cause of the seepage and to determine whether repairs are needed. Information to be gathered should include:

- When was the seepage first noted?
- Is the seepage water clear or cloudy?
- Is there evidence of material transport?
- Is the flow increasing?
- Is the seepage area expanding?
- Is the seepage exiting from or near the embankment?
- Was there a change in conditions that might have initiated the seepage (i.e. change in canal flows, seismic event, nearby construction activities, etc.)?
- Are there changes in the canal lining condition?
- Were there any canal cleaning activities?
- Is there any apparent embankment distress (i.e., animal burrows, dead/dying trees, embankment cracks or sloughs, etc.)?
- Are there deteriorated embankment penetrations?
- Are there nearby buried utility crossings (pipeline, culverts, etc.)?
- Have there been any new embankment penetrations?

With this information, plans for continued regular monitoring or preparation for repairs can be made.

2.6. Mitigation and Repairs

There are two basic approaches to address embankment seepage:

- Reduce or eliminate seepage
- Allow the seepage to continue but construct a filter along the seepage path to reduce the potential for internal erosion

Methods to reduce or eliminate seepage include liner repair, liner replacement, embankment reconstruction, grouting, or cutoff wall construction. These methods are preferred as they both improve canal safety and reduce seepage losses. In some circumstances, an extended canal outage to make embankment or liner repairs may not be feasible. If so, then a filter berm may be constructed in the interim until a more permanent repair can be made. Either approach must be designed by a professional engineer and reviewed by Reclamation.

Each of the seepage mitigation measures requires careful planning, analysis, and design. Selecting an appropriate seepage mitigation measure will vary from site to site (even along a given canal system). During selection and development of a seepage mitigation measure it is recommended that the operating entity work with engineers at the local Reclamation Area Office who may contact the Regional Office or the Technical Service Center (TSC) in Denver, Colorado for additional support.

2.6.1. Repair Existing Canal Lining

Canals may be lined with a multitude of materials. From original construction to maintenance repairs throughout the canal’s life, different types of linings may be encountered. Predominately, canals are either earth lined or concrete lined, although other lining systems are available and could be repaired with methods similar to those used for earth or concrete lined canals. Construction of a lining repair project must also consider the operational requirements of the canal. If a canal can be shut down and dewatered, there are many options available for repair implementation. If a canal can never be dewatered, repair methods will become very expensive and typically include the use of divers with limited alternatives available.

2.6.2. Existing Earth Lined Canal

Typically there are two types of earth lined canals. The first is very common, and is a simple excavated conveyance channel where local materials were balanced to provide fill for required embankments from sections requiring excavation (cut). The native soils in cut sections and the compacted soils in fill sections form the interior boundary of the canal prism. The second type of earth lined canal has an engineered “earth” or typically clay or lime stabilized lining material compacted as part of the original construction. Maintenance activities over time, if not careful, can damage or penetrate these types of engineered soil linings.

Over time, many earth lined canals will naturally seal with the deposit of silts and clays. Maintenance operations to remove vegetation or prepare for lining projects can disturb this type of “natural” barrier, and seepage causing piping of embedment materials can become an issue without the natural layer of protection.

Earth lined canals that require repairs, design upgrades for seepage mitigation, or safety improvements have several methods of repair available.

- **Repair "in-kind."** This method is simply to over excavate the identified canal section and replace with a compacted engineered clay liner. This type of repair should incorporate the installation of a geomembrane liner under the compacted clay material. Generally, a repair "in-kind" will have a life span of approximately 12 to 15 years before degradation or physical damage to the geomembrane will require repairs or replacement.

- **Lime Stabilization**. Lime stabilization is an excellent method for stabilizing embankments and for the prevention of vegetation growth on the canal lining. This method is not common as the availability of lime and specialized soil blending equipment is not widely used. Lime stabilization must be engineered to identify the optimum lime treatment required. Properly designed and constructed lime stabilized embankments have been seen to still show the sheep's foot compaction dimples after 40 years (Reclamation, 1987).

Depending on the reason identified to repair or upgrade an earth lined canal, a structural repair using concrete or other lining materials may be required. These methods are similar to repair methods for fixing existing concrete lined canals. See the following section with the consideration that foundation improvements may be needed depending on the soil conditions and previous maintenance activities completed on the earth lined canal.

2.6.2.1. Existing Concrete Lined Canal

A condition assessment must be completed prior to developing a lining repair or improvement project. This will determine if a minor repair or if a major lining replacement is required. See Reclamation 2017 (Concrete).

2.6.2.1.1. Crack Repair

Cracks in the canal lining need to be assessed to determine if they are stable, or if they are still developing. Many types of crack repair materials are available for both dry and underwater applications (Harrell and Klein 2015). Reclamation materials engineers or product manufacturers can provide guidance on available materials as well as relative durability (Figure 10).

Figure 10. Example of crack and joint sealing.

2.6.2.1.2. Lining Overlay Repair

When a canal lining is assessed, if vertical offsets or larger cracks are found, overlays may be considered. During this assessment, material properties should be considered to determine bonding capabilities between the original lining system and the available overlay materials. Overlays may be asphalt, concrete, geomembranes (Figure 11), or shotcrete. Cost and durability along with constructability should all be considered.

Caution should be used if the original lining system is masking a more serious embankment issue of foundation voids. In these cases, a removal of the original lining followed by a foundation repair should be completed. Then a new lining should be installed. Overlays can mask and delay a significant problem if not assessed and applied correctly.

Figure 11. Example of geomembrane placed over a distressed concrete lining.

Advantages of overlays are that other than minor site clean-up, no large scale demolition and disposal of waste lining is required. The original lining typically provides a base foundation for the new overlay. If there are foundation issues where the base is still moving, a more flexible overlay such as geomembrane materials should be considered. Shear, puncture resistance, ultraviolet (UV) degradation, and material joint welds must all be considered with the use of geomembranes. Shotcrete overlays are highly dependent upon the installer's skill and experience. Quality control measures must be taken to ensure appropriate mix designs as well as application rates (overlay thickness) are obtained. Grouted mattresses are also an option (Figure 12). These provide a durable structural repair that many times becomes effective if an underwater installation is required.

Figure 12. Example of a grouted mattress lining repair.

2.6.2.1.3. Panel Replacement Repair

If the damage is localized, saw-cut repair or complete panel replacement are both very effective (Figure 13). For this repair method, a section is either saw-cut and removed, or the entire concrete panel is removed and replaced. Foundation compaction and grading will often be needed after the old lining is removed. The new concrete is typically keyed into the existing lining segments. The joint between the existing and newly placed concrete needs to be considered. Typically a hydrophilic water stop is used.

Figure 13. Replacing individual panels.

Understanding the type of canal lining and failure mode will help identify an effective and cost efficient repair method.

See Reclamation's concrete repair manual for details on this type of concrete lining replacement for more detailed information (von Fay 2015) [www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Guide2ConcreteRepair2015_Final.pdf.](www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Guide2ConcreteRepair2015_Final.pdf)

Reclamation's Canal Operation and Maintenance: Concrete manual has more information on maintaining concrete lining and structures (Reclamation 2017 [Concrete]).

2.6.3. Install New Canal Lining

Figure 14. Completed concrete relined section of a canal.

Reclamation standards require a lining on all newly constructed canals. These linings can either be concrete or geomembrane, which is usually covered with shotcrete or concrete (Figure 14). This limits seepage and minimizes maintenance requirements related to vegetation and animals. Improved hydraulic characteristics are also achieved.

For concrete lined canals, during project development, designers can consider a range of design features that enhance the basic concrete lining and improve its performance and durability. These include structural reinforcement (rebar) or fiber reinforcement in the concrete mix, and a variety of lining materials that can be provided beneath the concrete. Even concrete lining systems have the potential for leakage, therefore foundation soils must be considered when developing a canal lining design.

Incorporating a geomembrane under a concrete lining may be considered. A geomembrane liner provides a secondary water/seepage barrier if foundation issues develop, or if the concrete lining is damaged. If the canal section is in a high risk location due to population, environmental concerns (i.e., earthquake locations) or future development, a concrete and geomembrane combination is recommended. Costs and benefits should be considered when developing the final lining design. Linings must be designed by a professional engineer and reviewed by Reclamation.

Longitudinal and transverse joint spacing must be considered in designing a canal lining system. All contraction joints must incorporate waterstops. Expansion joints are provided at the beginning and ending of all alignment curves. Expansion joints and thickened canal lining should be used at all canal structures (i.e. transitions, checks, turnouts, etc.). Care should be taken in determining spacing requirements for expansion joints as local weather conditions greatly impact the expansion characteristics of concrete lining panels. If this is not done correctly, buckling of the canal lining will occur requiring costly joint repairs.

2.6.4. Embankment Reconstruction

For small canals or when an extended canal outage can be scheduled, embankment reconstruction may be a viable alternative. The objective of embankment reconstruction is to excavate and remove the existing flawed embankment/shallow foundation materials and replace them with materials free of defects. The operating entity should work with Reclamation for additional support to develop an embankment reconstruction plan. The length of embankment reconstruction should be selected using the information collected during the seepage investigation. Side slopes and terminal ends of the excavation should be 3H:1V (horizontal:vertical) or flatter. Periodic benches should be formed in the excavation side slopes to avoid slip surfaces following fill placement.

The embankment may be reconstructed with the excavated materials obtained from removal of the existing embankment. Materials that contain organics or debris should not be used. Fill that has organics may attract burrowing animals. If the embankment is zoned, then materials from each zone should be separated and placed back to the original geometry. If it is found that the existing embankment/shallow foundation materials are too permeable, then an offsite borrow for finer grained/low permeability soils may be required. Minimum requirements for fill placement are below.

- **Prepare the excavation surface.** Before placing the fill, scarify the excavation's base to ensure proper bonding of the existing native soil or fill with the new fill to be placed. All debris, vegetation, and organic soil should be removed from the fill placement surface. Fill shall not be placed on frozen soil or within standing water.

- **Select the soil for backfill.** Fill to reconstruct the embankment should satisfy the original specifications (material gradation and plasticity index properties, moisture content, and compacted dry density). The excavated materials should be stockpiled and reused if possible. If additional fill is required, the imported material should be similar to the existing embankment materials. Where possible obtain materials with at least 35 percent fines, a plasticity index (PI) greater than 7, and low permeability characteristics. The fill should be free of trash, debris, over-sized material (i.e., cobbles or particles greater than 3-inches in size), organic material, or ice.

- **Moisture condition the fill.** Moisture condition the soil to achieve a uniform and optimum water content before placement. Slowly start to apply water to the fill while generously working the material. Clay soils should sit overnight to allow time for clay particles to fully absorb the added water. When working with clay soils, it is important to mix the soil so that the fill is free of clods.

Hand tests provide a quick and easy way to approximate the proper water content of the selected fill (Figure 15). Pick up a handful of soil and squeeze it.

Figure 15. Hand test for soil moisture.

- **Just right:** If the soil is moldable and breaks into only a couple of pieces when dropped on a hard surface, it is near the proper water content for compaction.

- **Too dry**: Dry soil produces dust and dry crumbles are apparent. If the soil is powdery and does not retain the shape from your hand, and/or if it shatters when dropped on a hard surface, it is too dry to compact well.

- **Too wet**: Wet soil is muddy and excessively deformable. If the soil bulges through your fingers to the outside of your hand when squeezed, leaves moisture on your fingers, and stays in one piece when dropped on a hard surface, it is too wet for compaction.

- **Use horizontal lifts.** Fill should be placed in horizontal lifts to optimize the compactive effort. Inclined fill lifts have the potential to cause slip/shear surfaces and should be avoided. The lift width should be as wide as possible to allow riding compaction equipment to be used and provide a safe working platform. In some cases, you may need to “overfill” the embankment and then cut the embankment to the desired slope.

- **Place and compact soil.** Proper compaction (densification) increases soil strength, reduces post-construction settlement and reduces permeability. For silty to sandy soils, use a heavy vibratory smooth drum roller. For clayey soils, use a heavy vibratory sheep’s foot roller. For hand operated tampers, or jumping jacks, plate and walk behind compactors, generally a loose (pre-compaction) lift thickness of less than 6 inches is recommended. For riding rollers, sheep foot compactors, or other heavy equipment, loose lifts typically should be in the range of 6 to 9 inches. Each lift should be compacted by making several passes with the compaction equipment or until the fill has little deflection under the load of the equipment. Apply uniform compaction across each lift area. Scarify the compacted lift before placing additional fill to provide bonding.

- **Test the compaction.** Sample(s) of the fill material should be provided to a laboratory for physical property and compaction testing. The results of the testing can be used to select the appropriate compaction equipment and establish in place moisture and density requirements. Generally embankment fill should be placed to at least 95 percent of the maximum laboratory dry density at a moisture content within two percent of optimum as determined by the Standard Proctor test American Society for Testing and Materials (ASTM) D698. Regular field density testing should be completed during the fill placement operations.

2.6.5. Seepage Cutoff Wall

When a canal outage is not available for liner or embankment reconstruction, a seepage cutoff wall may be a viable alternative. Cutoff wall technologies include; steel sheet piling, synthetic sheet piling, slurry walls (soil-bentonite, soil-cement-bentonite or cement-bentonite) and augered concrete secant walls (Figure 16). Limits of the cutoff wall should be carefully selected to extend vertically and laterally beyond the assumed seepage path(s) considering end around effects. In general, the cutoff wall should extend about 5 to 10 feet below the canal's invert. If there is a concern for seepage and internal erosion through deeper foundation materials, a fully penetrating cutoff may be required down to an impermeable unit.

Cutoff walls are a good alternative for "cutting off" flaws/seepage paths through the embankment and shallow foundation. Cutoff walls may also be used to reduce lateral seepage losses if a low permeability foundation layer exists. Cutoff walls will not reduce vertical seepage exiting from the canal prism.

Figure 16. Sheet pile cutoff wall.

2.6.6. Grouting

Grouting may also be used to reduce seepage and to fill voids beneath the canal lining and within the canal embankment and foundation (Figure 17 - Figure 20).

Figure 17. Grouting from the embankment crest.

Figure 18. Example of a grout manifold to allow for grout recirculation and control of flow and pressures to the grout hole.

Figure 19. Example of grouting beneath concrete lining to fill voids and seepage paths. Note laser levels used to monitor liner uplift.

Figure 20. Diver grouting voids beneath the liner. Note grout "bleeding" from vent hole further up the liner slope.

Grouting may be performed with the use of drill holes from the embankment surface or from core holes through the canal lining. The selection of an acceptable drilling method is critical for any grouting project. For example, the use of pressurized air or water can damage the embankment and/or foundation and should not be used. Grouting with the use of divers has recently been used, but can be very expensive. Without an extensive subsurface investigation, grouting is considered to be an "observational" method, as a number of injection locations might be needed before the seepage is reduced to an acceptable level. A well-planned grouting sequence is needed for any subsurface grouting project. Once grout is injected below the ground surface or beneath the canal lining, it is difficult to monitor where the grout travels. Batch weights and flow measurement devices may be used to record the volume of grout injected which can be an indicator of the degree of flaws in the embankment/foundation. Monitoring grout travel is usually done by monitoring adjacent grout holes and seepage locations. Grouting is considered to be successful once the seepage rate slows to an acceptable level.

Careful plans should be made to ensure appropriate equipment is used, a contractor is selected with adequate experience, the correct grout mix is selected for the intended purpose, and the appropriate personnel, testing, sequencing, and monitoring equipment are onsite during the work. Grout pressures should be carefully selected to avoid hydro-fracturing of the embankment or foundation materials or lifting and cracking the canal lining. Monitoring for surface movements is needed when grouting beneath canal liners. Grout pressures of 1 to 2 pounds per square inch (psi) have the potential to lift and fracture canal lining.

> Grouting should not be attempted without first consulting a grouting engineer from Reclamation’s TSC Geotechnical Services Division. The TSC can provide guidance on selecting appropriate grouting pressures, valve and gauge locations to control injection pressures, and equipment to monitor for surface movements.

2.6.7. Filter Berms

Filter berms consist of a “filter” placed over the seepage exit location and a weighted berm to both resist the seepage uplift pressures and to protect the filter materials from surface erosion (Figure 21). Generally, filter berms do not reduce the rate of seepage but rather reduce the potential for internal erosion. Filter berms will require expansion of the embankment footprint. Where right-of-way is not available at the embankment toe, a filter berm may not be a viable alternative.

The geometry/thickness of the weighted berm is a function of the expected uplift pressures at the base of the filter sand layer. The filter material properties and berm geometry will vary from site to site.

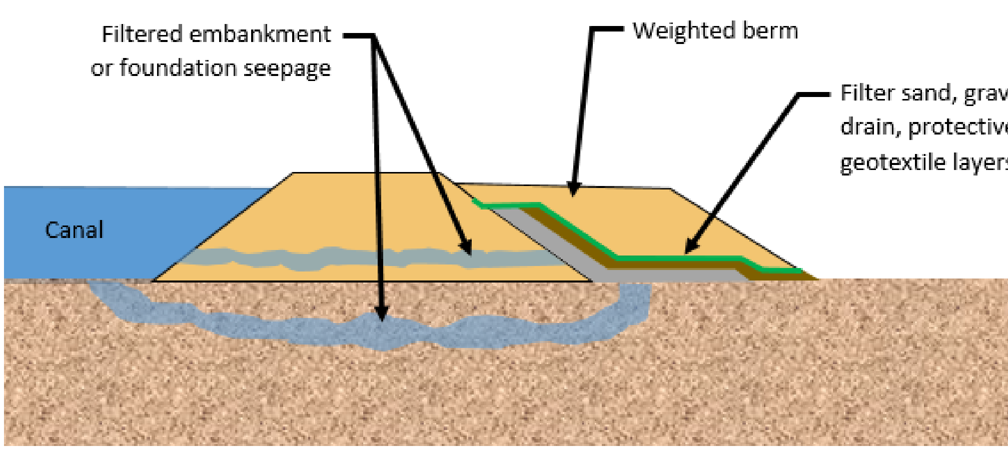

Figure 21. Typical filter berm configuration.

Select the filter materials appropriate for the base soils that might be eroded along the seepage path. Place filter sand against the embankment or foundation surface. Filter sand generally consists of an ASTM C33 concrete sand, with some modifications to the minus No. 200 sieve specification to allow for improved drainage. Then place a gravel drain layer over the filter sand to convey the filtered seepage to a drainage collection pipe or to daylight at the toe of the filter berm for monitoring. An ASTM C33 No. 67 coarse aggregate is typically used as a gravel drain material. When placed on a slope, the horizontal thickness of the sand and gravel layers are each about 3 to 4 feet-wide. The wider the zone the better to ensure the zones are constructable and are not contaminated during construction. The minimum vertical thickness should be about 12 to 18 inches when placed against a horizontal surface. Care should be taken when placing and compacting the filter materials to not over-compact the materials, as overcompacting reduces the drainage capacity or could break down the material, which might change the gradation properties.

A non-woven geotextile or filter sand zone should be placed over the gravel drain material to prevent the weighted berm material from contaminating the gravel drain.

3.Slope Instability

Slope instability is another form of embankment distress at Reclamation owned canals. Slope instability may progress slowly or occur suddenly. Slope failures may be classified into three groups:

1) Shallow sloughing type failures with no immediate threat of releasing the canal water

2) Deep seated failures through the embankment that might intersect the canal water

3) Global slip surface failures that might pass through both the foundation and embankment materials

This section discusses common causes of slope instability, how slope instability can lead to a canal failure (Figure 22), how an inspection and monitoring program can reduce the likelihood of failure, and methods that may be used to repair or stabilize an embankment.

3.1. Conditions Often Attributed to Slope Instability

Slope instability generally requires a change in condition or an initiating event such as a change in the groundwater conditions, an external force such as a seismic event, or a change in the slope geometry. Slope instability incidents and failures are most often attributed to areas where:

- The canal embankment is tall and/or steep
- The embankment and foundation soils have lower strength
- Historic landslides or slickensides[2] exist in the foundation
- Canal water or upslope drainages raise the groundwater table
- The canal lining has failed
- There is leakage from a buried utility pipeline
- Extended hydrologic events saturate the embankment materials
- A seismic event has produced strong horizontal ground motions
- A seismic event has caused liquefaction of the embankment or foundation materials that causes a reduction in strength

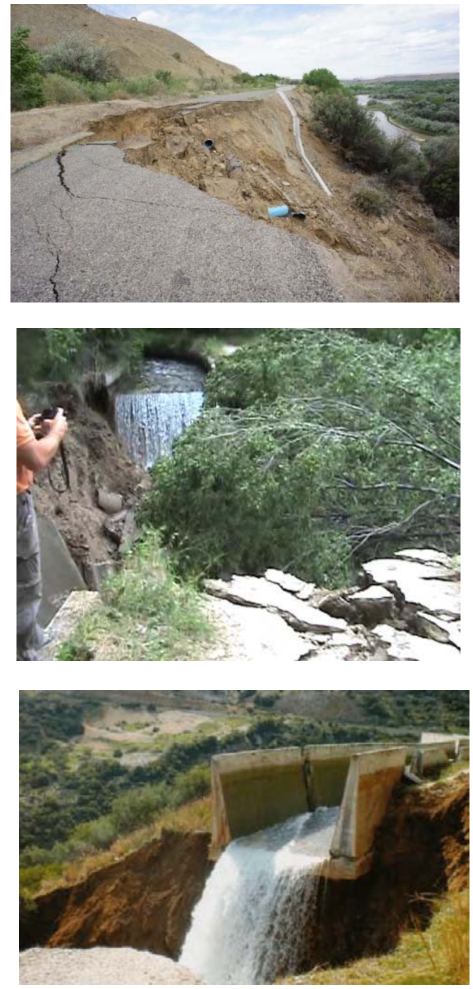

Figure 22. Examples of slope instability.

- Unauthorized embankment modifications have been made (i.e., excavations at the embankment toe)
- Modifications have been made to the slope above the canal
- There is heavy equipment or fill placement at the crest of the embankment
- There is rapid drawdown of the canal water surface

Slope instability is most often attributed to a rise in the groundwater level or phreatic surface. Changes in the groundwater level may be from canal leakage, subsurface drainage from sources upslope of the canal, or extended precipitation. As the groundwater level rises, the effective stresses along the potential slip surface are reduced. Effective stress anywhere along a potential slip surface is calculated as: (weight of soil x depth) minus (density of water x depth below the

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[2] A slickenslide is a smoothed surface from previous slope movement.

phreatic surface [h_w]). The strength of the soil along the potential slip surface is a function of the effective stress. As the effective stress decreases, so does the soil's strength (Figure 23).

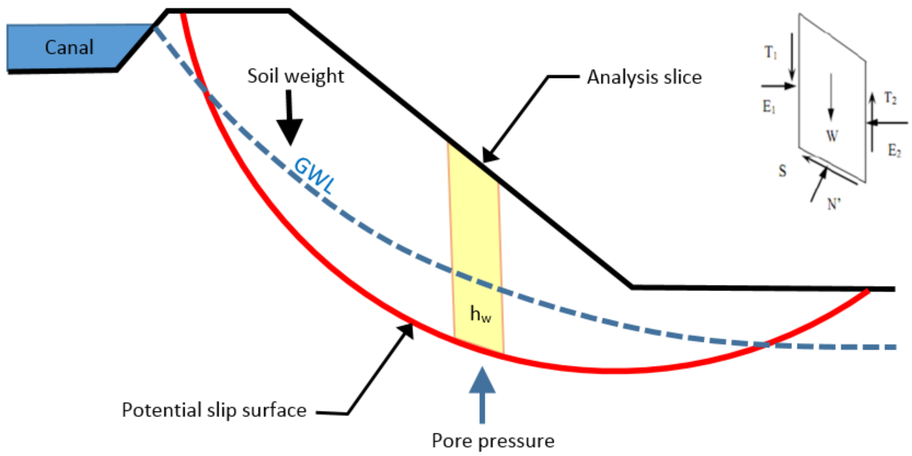

Figure 23. Schematic showing slope stability calculations.

Canal leakage and extended precipitation may also add weight to the soil above the potential slip surface. This added weight increases the driving forces and thereby reduces the safety factor.

Ground motions from an earthquake can produce horizontal forces that increase the driving stress along the potential slip surface. Ground shaking may also cause increased pore pressures in the saturated and partially saturated soils. The increase in pore pressures reduces the effective stress and thereby the soil's strength (i.e., liquefaction).

Modifications to the embankment slope may also induce a slope failure. Spoil piles and heavy equipment on the embankment crest can increase the driving forces along the potential slip surface (Figure 24). Excavations at the toe of the slope reduce the effective stresses at the toe and thereby reduce the soils strength and resisting forces. Careful considerations should be made prior to modifications to the existing embankment geometry.

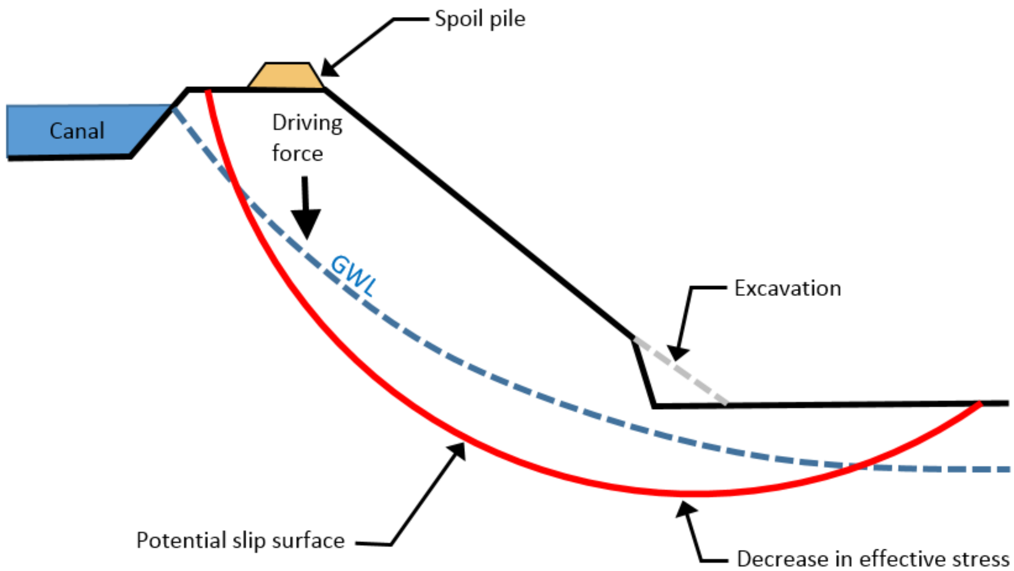

Figure 24. Schematic showing how slope instability is affected by embankment modifications.

3.2. How Slope Instability Can Lead to a Canal Failure

Once any of the initiating factors listed above occur, a slope failure may then progress slowly (years) or very quickly (seconds). Shallow sloughing type slope failures that do not intersect the canal water can shorten the seepage path and then a seepage failure can progress similarly to the internal erosion mechanisms described in Section 2. *Seepage and Internal Erosion*. It is also possible that a large slip surface could intersect the canal's prism but deformations are not large enough to release the water. Seepage along the slip surface and crack network may then develop as a scour type internal erosion failure.

If deformation lowers the embankment crest below the canal water surface elevation, then a rapid failure will likely occur. As canal water flows out through the failed section, the breach will widen until the canal is drained or diversions are stopped. Large, deep-seated slope failures which pass beneath the canal prism and embankment have the potential to cause a rapid failure. Figure 25 shows types of slope failure.

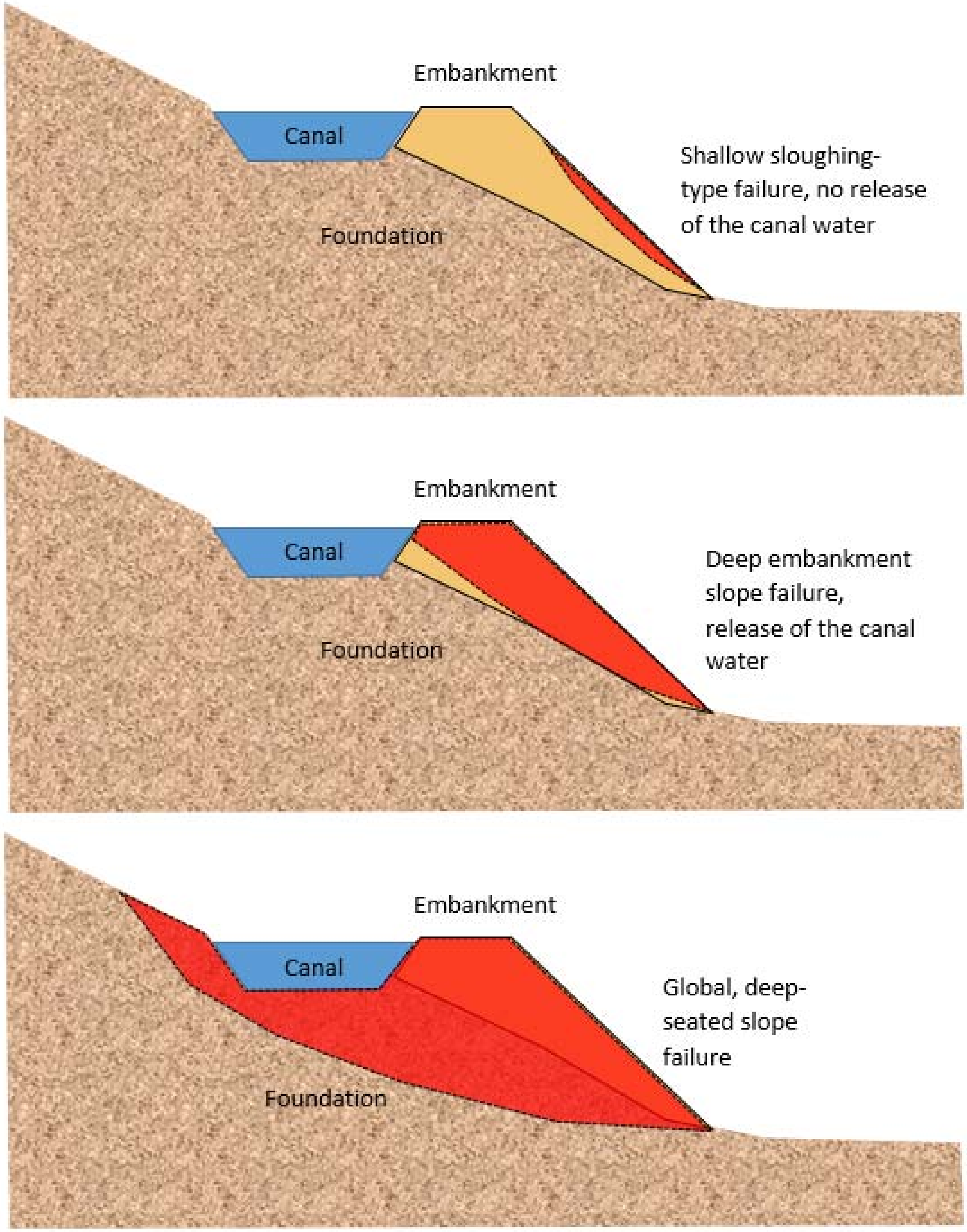

Figure 25. Types of slope failures.

3.3. Detection, Monitoring, and Investigations

3.3.1. Detection

Canal embankments should be inspected regularly for signs of slope instability (Figure 26). Common indicators that slope instability may be occurring include:

- Longitudinal cracks in the embankment crest
- Slumps or hummocky undulations in the embankment slope
- A vertical scarp or tear of the ground surface
- Offsets or deformation of the canal lining
- New seepage exiting the embankment slope or toe
- Mounding of soil at the embankment toe
- Leaning guardrails or signage poles on the embankment crest
- Leaning trees on the embankment slope or at the toe
- Raveling of rock materials at the toe of the embankment
- Visible differences when comparing historic aerial photos

Figure 26. Examples of signs of slope instability.

3.3.2. Documentation and Monitoring

Once slope instability has been detected, monitor regularly for any changes. Your monitoring and documentation should include:

- Dated photographs
- Drawings or sketches showing the instability locations/limits

- Rate of horizontal and vertical movements
- Surface markings for future canal operators

Canal operators should regularly visit each of the instability sites and record their observations in a standardized inspection checklist (Figure 27). Any changes should be highlighted and investigated further.

Figure 27. Tension crack monitoring.

3.3.3. Investigations

If slope instability develops or changes over time, conduct an investigation to better understand the cause of the instability and extent of the slide mass and to determine whether repairs are needed Figure 28). Information to be gathered should include:

Figure 28. Subsurface investigation.

- When was the instability first noted?
- What is the rate at which it is progressing?
- Are there changes in the canal lining condition?
- Are there any changes to the seepage conditions?
- Was there a change in conditions that might have initiated the instability (i.e., a change in canal flows, seismic event, nearby construction activities, etc.)?

Begin your site investigation by contacting a geotechnical engineer or geologist from Reclamation’s Regional office or from a local engineering firm. A review of the available geologic mapping information and site reconnaissance should be completed. With this information, an estimation of whether the movement is in the foundation soils or within the embankment can be made.

It may also be prudent to complete a subsurface investigation to collect soil samples for index and strength testing and to install inclinometers and/or observation wells. Inclinometer casing can be installed in the drill hole (Figure 29). When instrumentation is inserted into the casing, the location or depth of the slip surface can be determined. Measurements over time can be used to determine the rate at which the movement is occurring. The observation wells can provide information regarding the groundwater level and indicate whether seepage is occurring along the slip surface.

Figure 29. Inclinometer casing.

It may also be useful to install surface survey monuments to monitor the rate and direction of the slide mass movement. The surface monuments generally consist of a survey cap or length of rebar anchored in concrete in a shallow drill hole.

The collected information can be used to develop plans for regular monitoring or preparation for repairs.

3.4. Mitigation and Repairs

Basic approaches to address embankment instability are:

1) Take measures to reduce the potential for groundwater level changes to
2) Reconstruct the embankment to remove the slide mass
3) Use reinforcing members to stabilize the slope, thus improving the foundation strength
4) Modify (flatten) the slope geometry.

Methods to reduce the potential for groundwater level changes include liner repair, liner replacement, and improved drainage to avoid ponding of water upslope of the canal. In some instances, the slide mass will need to be removed. Excavation should remove all of the material within the slide mass and extend some distance beyond the slip surface. An extended canal outage will be required for embankment reconstruction. As an alternative to embankment reconstruction, various slope stabilization methods may be considered.

Each of the embankment instability mitigation measures requires careful planning, analysis, and design. Selection of an appropriate instability mitigation measure will vary from site to site (even along a given canal system). Work with engineers at the local Reclamation Area Office who may contact the Regional Office or the TSC to select and develop instability mitigation measures.

3.4.1. Repair and Installation of Canal Lining

See Section 2.6.1. *Repair Existing Canal Lining* and Section 2.6.2. *Install New Canal Lining.*

3.4.2. Regrade and Improve Drainage

Surface runoff that impounds against the upslope side of the canal can cause a change in the groundwater level. Drainage swales and ditches should be constructed to route runoff to culverts, over chute crossings, or designated discharge locations into the canal.

3.4.3. Embankment Reconstruction

If movement along the slip surface is more than a couple inches, then embankment reconstruction will likely be required. The excavation should extend beyond the slip surface to remove displaced and weakened materials, preferential slip surfaces and/or potential seepage paths (Figure 30). Benching or “stair stepping” the excavation should be used to minimize the potential for preferential slip surfaces between the foundation and embankment materials (Figure 31). The embankment reconstruction should extend at least 10 to 20 feet laterally beyond the limits of the slide mass. The termination of the excavation should also be benched with slopes between the benches no steeper than 3H:1V. New fill placement should be done similarly to what is described in Section 2.6.3. *Install New Canal Lining.*

If there is sufficient right-of-way, the embankment slope should be flattened. Selection of an appropriate slope angle should be done through the use of slope stability analysis.

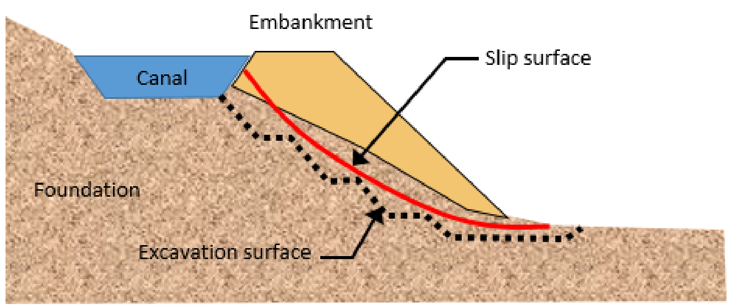

Figure 30. Stepped excavation to completely remove the slide mass.

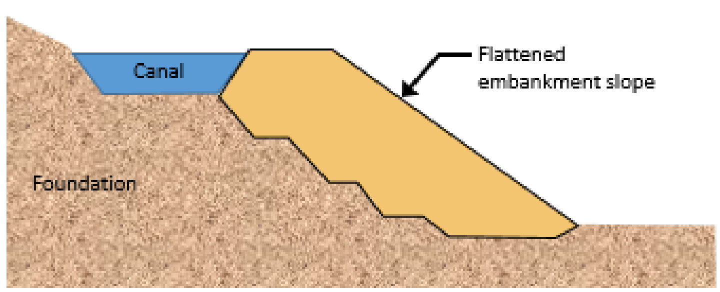

Figure 31. Reconstructed embankment.

3.4.4. Slope Stabilization

Slope stabilization may be accomplished by a number of methods and technologies (Figure 32) including;

- Tie-backs and grouted anchors
- Soil nails
- Geosynthetic slope reinforcement products
- Foundation shear key
- Stability berm/buttress

Each of the slope stabilization alternatives require careful planning and design by a qualified geotechnical engineer.

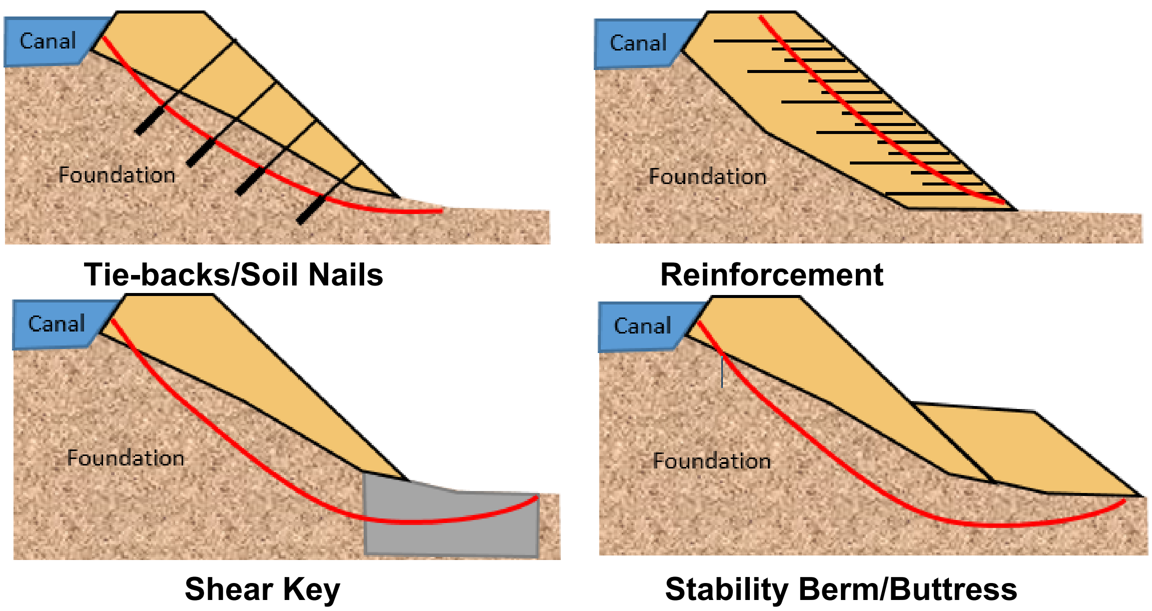

Figure 32. Examples of embankment stabilization methods.

4. Surface Erosion

Surface erosion is another common occurrence at canals. If surface erosion is not addressed early, it can worsen rapidly and if ignored can lead to a canal failure. This section discusses common causes of surface erosion, how surface erosion can lead to a canal failure, how an inspection and monitoring program can reduce the likelihood of failure, and methods that may be used to repair or stabilize an embankment.

4.1. Common Causes of Surface Erosion

Surface erosion is a naturally occurring process that affects all landforms (Figure 33). Surface erosion is most often caused by channelization of runoff. Precipitation collecting on the embankment will eventually flow down the embankment slopes causing erosion. Small rills will eventually enlarge to form gullies. The erosion features can become quite large during a single extended/high intensity rainfall event or can progressively enlarge from repeated precipitation events if the areas are not repaired. Additional factors that contribute to the occurrence of surface erosion include:

Figure 33. Examples of surface erosion.

- Bends and changes in the canal alignment
- Changes in the embankment slope angle and length
- Areas where the embankment abuts to a natural ground outcropping
- Slopes with very little vegetation cover
- Areas with low density fill
- Areas where fine granular soils exist at the surface
- Notches placed in the crest safety berms to allow drainage
- Collapse of shallow animal burrows
- Incised vehicle trails (dirt bike/all terrain vehicle [ATV] trails)
- Animal and foot traffic trails
- Areas of high velocity flow (constrictions in the canal cross section)

- Upslope drainages entering the canal

- Excavations or modifications to the embankment geometry by the public

- Surface erosion can be caused by wind (usually at a much slower rate than erosion caused by runoff)

4.2. How Surface Erosion Can Lead to a Canal Failure

Surface erosion can be a slow process or can occur very quickly during a high intensity rainfall event. As the erosion gullies deepen, the effective width of the embankment is reduced. The shortened seepage path can then allow internal erosion to progress as described in Section 2. Erosion can also cause localized steepening of the embankment slope. The steeped areas can then experience slope instability and progress to failure as described in Section 3.

Erosion gullies may also headcut (actively erode at the head or upstream end of the erosion) through the embankment crest. If the base of the erosion gully extends below the canal water surface, then canal water can flow out through the erosion feature and rapidly enlarge to cause a breach.

4.3. Detection, Monitoring and Investigations

4.3.1. Detection

Canal embankments should be inspected regularly for signs of surface erosion. Common indicators that surface erosion may be occurring include:

- Visual erosion features on the embankment slopes
- Sediment deposition at the toe of the embankment slope
- Flow concentrations during a rainfall event

4.3.2. Monitoring and Documentation

Once surface erosion has been detected, monitor regularly for any changes. Monitoring and documentation should include:

- Dated photographs
- Drawings or sketches showing the erosion locations/limits
- Rate of downward and lateral erosion
- Surface markings for future canal operators

Canal operators should regularly visit each of the erosion sites and record their observations in a standardized inspection checklist. Any changes should be highlighted and investigated further.

4.3.3. Investigations

In instances where surface erosion develops or is changing over time, conduct an investigation to better understand the cause of the erosion and to determine whether repairs are needed (Figure 34). Information to be gathered should include:

- When the erosion was first noted
- The rate at which it is progressing
- The depth and width of the erosion gullies
- Recent weather history
- The embankment soil properties (granular, silty, clayey, etc.)
- Survey of the area to identify any low areas
- Record of any modifications to the embankment slopes

Figure 34. Surface erosion investigations.

4.4. Mitigation and Repairs

Surface erosion should be repaired as soon as it is detected. If ignored, the erosion gullies will enlarge and pose a threat to the canal’s integrity. The following sections describe measures to consider for mitigating or repairing surface erosion.

4.4.1. Embankment Crest Grading

Precipitation which collects on the crest will eventually channelize and flow down one of the embankment slopes. The embankment crest should be sloped to direct the runoff toward the most stable embankment slope. If the exterior slope is tall and steep, it may be preferable to slope the crest toward the canal prism. If the exterior slope is short, flat, or has sufficient erosion protection, it may be preferable to slope the crest toward the exterior. A slope of 1 to 2 percent is adequate to direct the runoff.

Notches in spoil piles or safety berms should only be made where there is adequate slope protection where the runoff will be channelized. Armored swales may be required where notches in the berms are formed.

Fill collapsed animal burrow features as soon as possible. These collapse features will collect and channelize runoff leading to the development of erosion gullies.

4.4.2. Erosion Repair

Erosion damage should be repaired as soon as possible. Erosion gullies deeper than one foot should be excavated and backfilled with compacted material. The erosion gullies should be excavated with 1H:1V side slopes or flatter and a base width of at least 3 feet. Fill should then be placed in lifts starting at the toe of the slope. Jumping jack or walk-behind compactors may be required. Excavator attachments may also be used to compact the fill in the excavated erosion gullies. Simply dozing materials into the erosion features will leave loose, uncompacted material that will quickly redevelop into a new erosion feature.

Repair of erosion gullies may require additional material to fill the erosion features. Use borrow sources with a higher clay, gravel and cobble content. Granular materials predominantly comprised of silt and sand sized particles are most prone to surface erosion and should be avoided in repair areas. Figure 35 shows how an erosion gully should be excavated and backfilled.

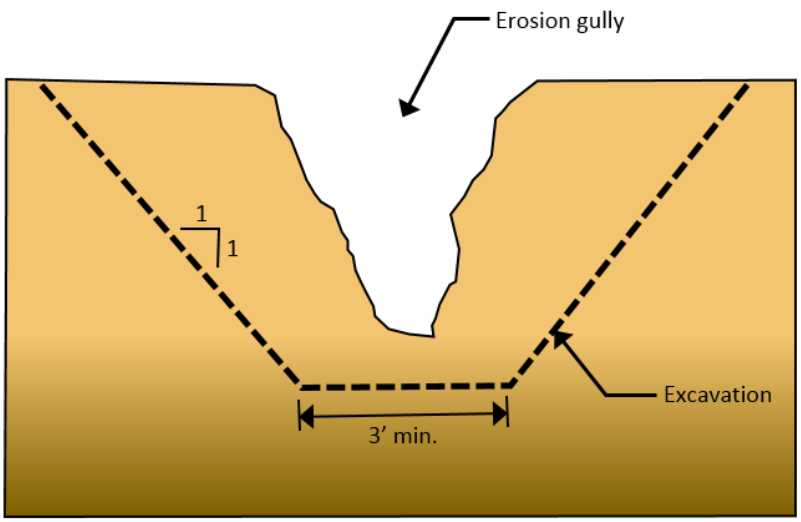

Figure 35. Suggested erosion gully repair.

Erosion rills that are less than a foot deep can be repaired without additional fill material. The affected area should be scarified with the teeth of an excavator bucket or dozer, and the area should then be rolled with heavy tracked equipment such as a dozer or excavator attachment. The area should be compacted to minimize the potential for future surface erosion. Cross tracking the slope should be avoided as track indentations parallel with the slope can lead to forming new erosion gullies (Figure 36 and Figure 37).

Figure 36. Repairing slope with an excavator attachment

Figure 37. Proper and improper method for tracking slopes.

4.4.3. Erosion Control Measures

When surface erosion becomes a continual problem erosion control measures may be considered. Selection of the appropriate erosion control measure will be a function of the embankment geometry, soil properties, climate and rainfall characteristics, and potential for vegetative cover. Erosion control products and measures include:

- Riprap slope protection
- Benching
- Armored drainage swales
- Check dams and wattles
- Erosion control matting (ECM)
- Plastic sheeting
- Geocell
- Soil binders and tackifiers
- Temporary and permanent vegetation
- Surface roughening
- Pipe slope drains

These useful references can help you select an appropriate erosion control measure. Reclamation engineering staff are also available to aid in the erosion control design.

Bureau of Reclamation, 2006. *Erosion and Sedimentation Manual.* www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Erosion%20and%20Sedimentation%20Manual.pdf

Natural Resources Conservation Service, 2008. *Urban Soil Erosion and Sediment Control.* www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs141p2_034363.pdf

Clean Water Services et al., 2008. *Erosion Prevention and Sediment Control Planning and design Manual.* www.cleanwaterservices.org/media/1464/erosion-prevention-and-sediment-control-manual.pdf

Tennessee Department of Environment and Conservation, 2012. *A Stormwater Planning and Design Manual for Construction Activities.* tnepsc.org/TDEC_EandS_Handbook_2012_Edition4/TDEC%20EandS%20Handbook%204th%20Edition.pdf

5. Emergency Preparedness, Intervention, and Communication

5.1. Emergency Preparedness

Even with the best O&M practices, incidents and failures occur. Preparation is key to being able to quickly intervene and stop a developing incident from becoming a failure. Intervention involves detecting the issue and physically intervening when necessary. The previous chapters have focused on detection, monitoring, and long-term mitigation. This chapter focuses on preparedness activities that should include:

- Stage filter and embankment materials near the site
- Identify potential borrow sources
- Identify equipment and operators that can quickly respond to the site
- Identify construction equipment travel routes
- Identify hydraulic control structures that might be used to isolate a segment of canal

- Use your Standing Operating Procedures (SOP) to identify where canal diversions will be stopped and the rate at which the flows can be decreased to avoid damage elsewhere

- Gain an understanding of the flow time and volume of water that might remain in the canal after diversions have been stopped

5.2. Intervention

Take timely actions to address seepage-related incidents to avoid a canal failure (Figure 38). Progression of an internal erosion failure from new seepage to a full breach of the canal embankment can take less than an hour. Loose and erodible embankment materials are most susceptible to a rapid failure. If new seepage is noted:

- Lower the canal water surface by opening downstream checks, operating turnouts and wasteways, or reducing diversions

- Increase inspections and monitoring

- Monitor for changes in the flow rate (are conditions worsening?)

- Look for sediment transport (is it clear or cloudy?)

- Begin to haul materials to the site

- Mobilize construction equipment and operators

- Place material over the seepage exit. In some instances, it may be more successful to place materials in the canal prism to block the seepage entrance

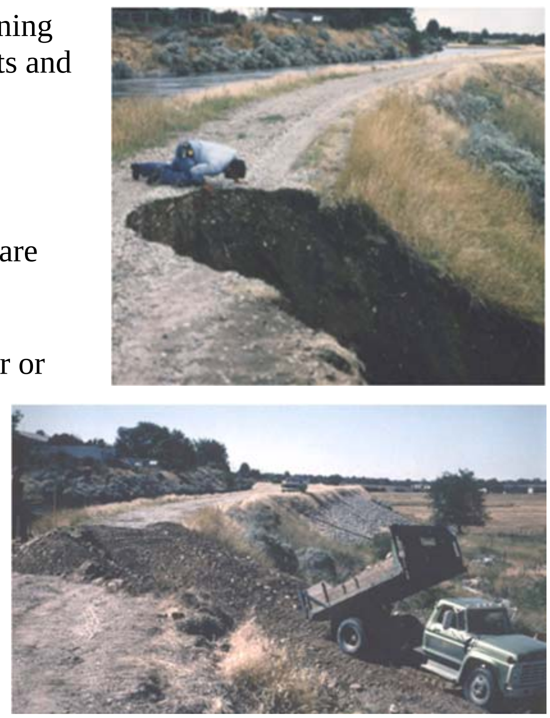

Figure 38. Monitor and act.

- If a sand boil develops construct a ring dike (similar to Figure 9 in Section 2.5.2. *Documentation and Monitoring*) to raise the tailwater to lower the exit gradient and to capture the eroded sediments.

If embankment instability appears to be progressing or there is the potential for a rapid failure:

- Lower the canal water surface by opening downstream checks, operating turnouts and wasteways, or reducing diversions

- Haul materials to the site that can be used to stabilize and buttress the toe of the embankment slope

- Remove any heavy equipment or spoil piles that may have initiated the slope movement

- Backfill any excavations at the toe of the slope that may have initiated the slope movement

- Where freeboard allows, make excavations on the slide mass to reduce the driving forces. Only operate equipment on or near the slide mass if it is safe to do so.

5.3. Communication

If a seepage or slope instability incident is worsening and/or there appears to be an imminent threat of failure, the operating district should initiate the Emergency Action/Management Plan (EAP or EMP). Warning should be issued to persons in the inundation area as soon as possible to allow for evacuation. Warning should be issued to those residents in the immediate vicinity of the canal first. Local emergency and law enforcement personnel should then provide warning to those in the remaining inundation area. Those providing warning should describe the severity of the potential flooding and the best route to leave the area to the best of their ability.

Reclamation’s Area Office and Regional staff are available to process and issue information to the community.

5.4. Repair of a Failed Embankment

If a failure occurs, the operating district should make every effort to fill the breached section as quickly as possible to reduce the volume of water that is released. Once the outflows have been stopped, the operating district should expect a forensic investigation be completed to understand the cause of the failure. This investigation may take several days to complete. During the shutdown, conduct a thorough inspection of the remaining canal length to determine whether it is safe to restore canal operations. Political pressure may also slow the repair and reoperation schedule. This delay will almost certainly be longer if a loss of life occurs or if there are significant economic damages. Reclamation’s Area Office and Regional staff are available to help communicate the importance of restoring canal operations to avoid further agricultural damages.

Preparation and reconstruction of the embankment should follow the recommendations in Section 2.6.3: *Embankment Reconstruction*. Work with Reclamation for additional support to develop an embankment reconstruction and reoperation plan.

5.5. Appreciating Canal Breach Flooding Potential

In response to recent canal breach events, Reclamation has performed physical and numerical model testing to determine the factors that affect the severity of canal breach floods (Wahl and Lentz 2011). Some of the key findings from those studies:

- **Canal size**. Large canals (higher flow capacity) have the potential to produce more severe flooding.

- **Erodibility of canal embankment soils**. Soils that are predominantly sandy or silty with low clay content and low plasticity can allow an embankment to fail so rapidly that intervention is impossible—even if a failure is detected in its early stages. Failure can also occur so fast that the canal water level does not drop significantly during breach formation, so maximum head is available to drive water through the breach. Differences in erosion rates between highly erodible and more erosion resistant soils can be 1000:1 or greater.

- **Depth and velocity characteristics of canals**. Canals that have a relatively flat bed slope and low velocity (a low *Froude* number) have the most potential to produce floods that are many times larger than the normal canal flow rate. Conversely, canals that have steeper channel slopes and higher flow velocities (larger *Froude* numbers) have somewhat less potential to produce large outflows.

- **Depth-to-width ratio of the canal**. Canals that have a large depth-to-width ratio (i.e., a relatively narrow flow cross section) have greater potential to produce a large peak outflow rate during a breach event. Canals that are relatively wide and shallow have somewhat less potential to produce a large peak outflow.

- **Length of the canal reach between check structures and the proximity to nearby check structures**. Check structures may offer a location at which canal flow can be shut down during an emergency, if there is enough time to intervene. The distance between check structures is an indicator of the water volume that is still available to flow through a breach after such intervention has been implemented. Long reaches between check structures have the greatest potential to produce large (and sustained) breach outflow floods.

Wahl (2016) provides a procedure for estimating the flooding potential from a canal breach, considering the influence of many of the factors listed above. While any and all canal breaches are potentially serious, examine the canal reaches so that you know those that have the greatest potential to cause severe flooding—before the canal breaches.

Two other factors not specifically listed above are very important to consider, but are not explicitly incorporated into the general procedures developed through Reclamation's research. These factors must be considered on a case-by-case basis:

- **The proximity and number of people and infrastructure resources that would be at risk during a canal flood**. Canal incidents that occur immediately adjacent to heavily populated areas should be treated with the greatest importance.

- **Topography outside of the canal at the breach site**. If the canal is elevated above the surrounding area, the flooding risk is greater than a situation in which the canal is at or below the elevation of the surroundings. Nearby channel features that may keep the flood flows concentrated after they leave the canal should also be considered. If the surrounding area if very flat, flooding intensity will decrease rapidly as the flood spreads out.

6. References

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