Figure 84.—An embankment dam in Mississippi constructed of dispersive clay soil, failed on first filling with low reservoir level. Failure was likely caused by cracks from differential settlement, hydraulic fracture, or poor compaction about the outlet works conduit. This embankment dam had no filter.

Figure 85.—This embankment dam constructed with dispersive clays failed on first filling of the dam.

Soils with low plasticity indices are also more likely to experience rapid internal erosion than soils with higher plasticity, as water flows through the soils or along an interface between the soil and an object, such as a conduit or bedrock in contact with the soil. The failure of Teton Dam in 1976 in Idaho illustrates the speed with which failure can occur in internal erosion involving low plasticity embankment soils.

Some embankment dams contain zones of broadly graded soil with sufficient fines content to be considered low in permeability, but the soils are found to be subject to suffosion from internal instability. The low resistance to internal erosion of broadly graded soils is well documented in references by Garner and Sobkowicz (2002), Sherard (1979), and LaFleur, Mlynarek, and Rollin (ASCE, 1989). The internal instability of these soils results from the ability of finer soil particles to be mobilized between larger particles in these broadly graded soils. This soil movement, termed suffosion, results in sinkholes, if erosion progresses long enough. Designing filters using current criteria has been shown to be effective in blocking internal erosion in these soil types.

Dispersive clays differ from "normal" clays because of their electrochemical properties. The paper by Sherard, Decker, and Ryker (1972b, p. 589) has good discussions on the reasons dispersive clays' chemistry influences their behavior so strongly. From that paper,

> The main property of the clay governing the susceptibility to dispersion piping is the quantity of dissolved sodium cations in the pore water relative to the quantities of other main basic cations (calcium and magnesium). The sodium acts to increase the thickness of the diffused double water layer surrounding individual clay particles and hence to decrease the attractive force between the particles, making it easier for individual particles to be detached from the mass.

Flow through cracks in dispersive clays can quickly erode the cracks and lead to rapid enlargement of the cracks. Failures caused by internal erosion in dispersive clay dams are common. Several case histories presented in appendix B discuss failures associated with internal erosion in dispersive clay soils. The intent of chimney filters and filter diaphragms around conduits is to intercept flow occurring in cracks in the embankment dam, to seal the flow of water by developing a filter cake at the face of the filter. See section 6.4 for additional discussion concerning filters.

Identifying dispersive clays requires special tests that are not always routinely performed. The tests most commonly used for identifying dispersive clays are the crumb test (ASTM D 6572), the double hydrometer test (ASTM D 4221), and the pinhole test (ASTM D 4647).

The pinhole test is a direct measure of the erodibility of a soil. A 1-mm hole is formed in a specimen of soil, and water is forced through the hole at increasing heads. A dispersive clay soil will erode rapidly under a low 2-inch head within 10 minutes of flow initiation. A non dispersive clay usually undergoes little erosion, even under sustained flow through the hole under a head of up to 40 inches. The test is performed using standard procedures established in ASTM D 4647.

Two tests have been developed to study the erosion characteristics of soil in addition to the pinhole test, which is used exclusively to evaluate dispersive clays: the slot erosion test and the hole erosion test (Wan and Fell, 2004). Australian researchers at the University of New South Wales developed these tests, which are not widely used in the United States. The erosion characteristics are described in these supplemental tests by the erosion rate index, which indicates the rate of erosion due to fluid traction, and the critical shear stress, which represents the minimum shear stress when erosion starts.

Results of the two laboratory erosion tests are strongly correlated. Values of the erosion rate index span from 0 to 6, indicating that two soils can differ in their rates of erosion by up to 6 times. Coarse grained soils, in general, are less erosion resistant than fine grained soils. The erosion rate indices of coarse grained soils show good correlation with the fines and clay contents, and the degree of saturation of the soils. The erosion rate indices of fine grained soils show moderately good correlation with the degree of saturation. The absence of soils with the clay minerals called smectites and vermiculites, and apparently the presence of cementing materials, such as iron oxides, improve the erosion resistance of a fine grained soil.

The hole erosion test is proposed as a simple index test for quantifying the rate of internal erosion in a soil, and for finding the approximate critical shear stress corresponding to initiation of internal erosion. Knowledge of these erosion characteristics of the core soil of an embankment dam aids assessment of the likelihood of dam failure due to internal erosion.

See the NRCS's *Dispersive Clays* (1991) for more detailed discussions of methods for identifying dispersive clays. Another reference (Sherard, Dunnigan, and Decker, 1976, pp. 287-301) also discusses identification of dispersive clays.

A filter around conduits is important where dispersive clays are used for embankment dam construction. The dimensions of a filter should be increased because dispersive clays are so dangerous to the integrity of an earthfill. An embankment chimney drain/filter that extends completely across an earthfill, from one abutment to the other, extending upwards to the normal pool height or higher, is often used. See chapter 6 for design and construction of filters.

Treating dispersive clays with chemical amendments may be effective in reducing their erodibility, but this alternative may be costly, except with specific embankment zones. Treating dispersive clays used as backfill in cutoff trenches and on the outer slopes of embankments are examples. Several chemicals have been used to modify dispersive clays. The most common additive is hydrated lime. The NRCS reference on dispersive clays (NRCS, 1991) discusses chemical amendment in more detail. However, the designer is cautioned that treatment with lime will increase the material's brittleness.

Chimney filters that coincide with a filter diaphragm or collar around conduits are the preferred method for preventing failures associated with dispersive clays. Embankment dams constructed of dispersive clays should use a substantial filter diaphragm around the conduit, if a chimney filter is not included in the design of the dam.

5.4 Frost susceptibility and ice lenses

Some soils, especially silts, are frost susceptible. When conduits are in contact with frost-susceptible soils, large ice lenses may form in the soil if the conduit is exposed to freezing temperatures. When these ice lenses melt, voids are left in the earthfill that are subject to internal erosion, if they are connected to the reservoir and continuous in a direction transverse to the embankment dam. This is a suspected failure mode in the Anita Dam and Loveton Farms Dam failures (see appendix B) and Kelso Dam in southern Ontario, Canada (Milligan, 2003, pp. 786-787). Guidance concerning frost susceptibility and ice lenses includes:

- *Process of ice lens formation.*—When wet soil freezes, most of the water in the soil pores becomes ice, and it expands about 10 percent (Sowers, 1979). However, in frost-susceptible soils, it has been found that not all of the water freezes. Capillary soil water may remain in liquid form at temperatures of 28 °F, and some liquid water may even still exist at temperatures as low as -4 °F (Penner, 1962, p. 1). When the water in the larger pores freezes, the moisture content in the soil is reduced, and unfrozen capillary water in the surrounding soil tends to migrate toward the frozen zone because of surface tension. The frozen water becomes an ice lens, which will draw water from the surrounding soil as long as unfrozen water is available and the temperature at the lens remains cold. The result is that the ice lens grows larger, and the total expansion of the soil is much larger than that which would occur with the expansion of the original amount of water present in the soil.

  The growth of these ice lenses creates very large pressures in the soil, creating frost heave within the embankment dam. These forces can damage rigid conduits and can cause excessive deformation of flexible conduits resulting in pathways for internal erosion. When the ice lens defrosts, it can create a void or low density zone that can initiate the internal erosion process.

- *Frost-susceptible soils.*—Silts and silty soils are the most frost susceptible, because the voids can be of capillary size, and the permeability of the soil is sufficient for migration of pore water. Fine grained clays are not conducive to formation of large ice lenses, because they are too impermeable to allow substantial migration of the soil water. Sands and gravels with less than 3 percent fines content (material finer than 0.075 mm, No. 200 sieve) are not generally frost susceptible (Reclamation, 1998a, p. 54).

  Thousands of embankment dams constructed of frost-susceptible materials have experienced no apparent problems. For both case histories in appendix B where ice lenses are suspected as contributing factors in dam failure, the conduits were relatively large metal pipes. Such large pipes may allow sufficient cold air flow through them to cause the adjacent embankment soils to freeze, while the heat in flowing water in smaller conduits may minimize the problem. Also, the metal pipes are relatively thin, so cold temperatures are transmitted to the surrounding soil relatively quickly. Cold temperatures would take longer to affect the soils surrounding conduits with thicker concrete walls.

- *Design considerations.*—Backfilling adjacent to conduits with clayey materials would minimize the potential for formation of ice lenses in the embankment dam. Also, construction of a properly designed filter diaphragm or collar near the downstream end of the conduit would control seepage along the outside of the conduit and minimize the potential for failure by internal erosion.

Chapter 6

Filter Zones

Zones of designed filter material have become the accepted method of preventing failures caused by uncontrolled flow of water through the embankment materials and foundation soils surrounding a conduit through an embankment dam. This chapter discusses the theory behind the concept for using filter zones to prevent erosion of earthen embankments near conduits caused by the uncontrolled flow of water through soils surrounding conduits that penetrate the embankment.

The type and configuration of the filter zone depend on site conditions and soils used in the embankment dam. Three basic designations for filter zones associated with conduits are discussed: filter diaphragms, filter collars, and chimney filters. Examples of typical designs used by the major design agencies are included.

6.1 Theory of filter seal development

The concept behind the function of a filter in sealing a concentrated flow was developed largely from laboratory experiments under the guidance of Sherard as reported in several references (Sherard, Dunnigan, and Talbot, 1984). Figure 86 (top) is reproduced from this reference, and it illustrates filter cake development in the laboratory experiments. Figure 86 (bottom) shows the action of the filter in sealing a concentrated leak in an embankment dam.

6.2 Federal agency policy on filters for conduits

The following policy concerning filter zones has been summarized from three of the major federal agencies that have been traditionally involved with embankment dam construction:

- *Bureau of Reclamation*.—From Reclamation's, *Embankment Dams—Embankment Design* (1992, p. 21):

> Structures through embankments should be avoided unless economics or site geology dictates their use. If they are used, the primary means of controlling

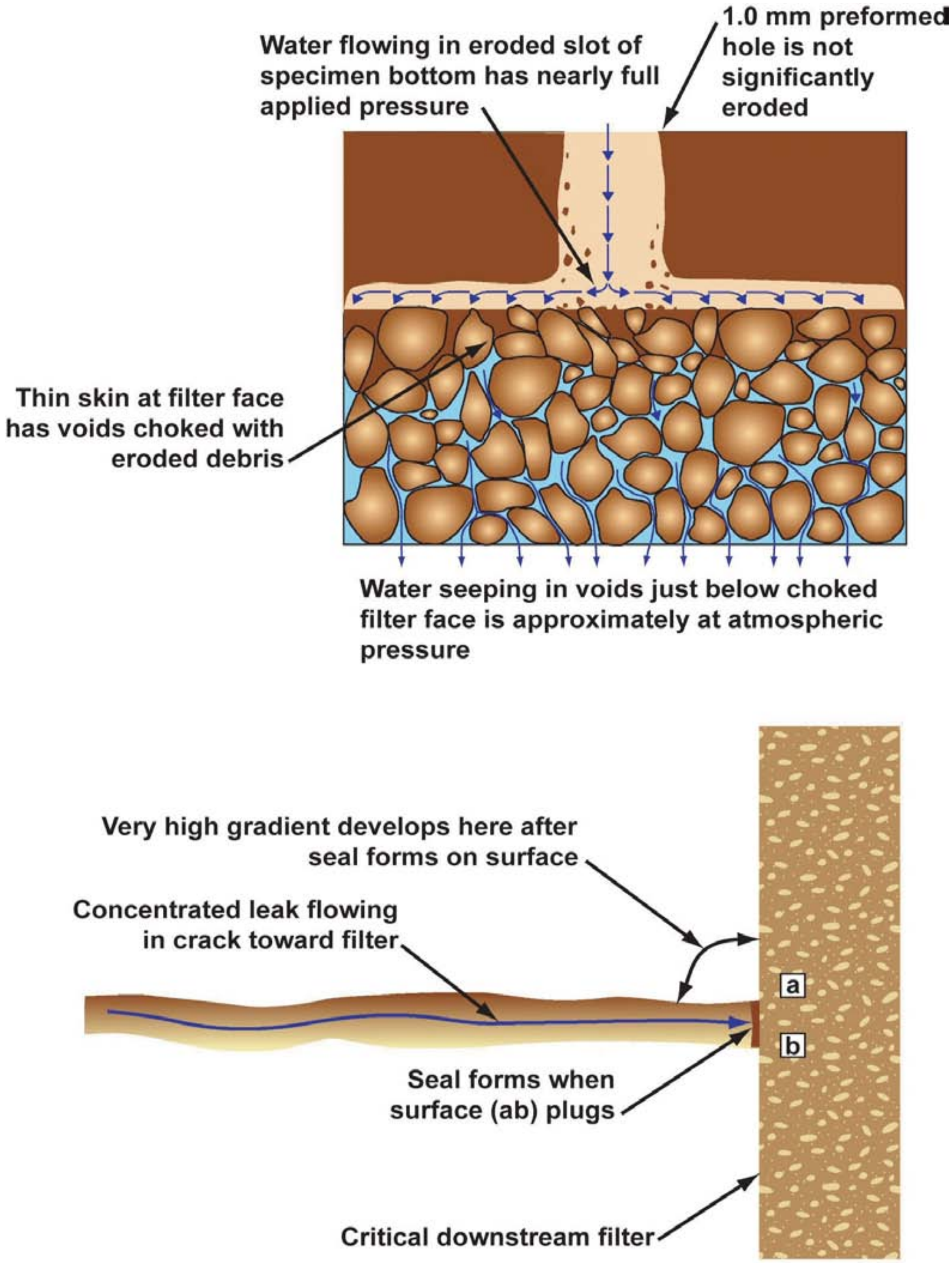


Figure 86.—Illustration of the mechanism of development of a filter seal resulting from the accumulation of eroding soil particles at the face of a designed filter zone, showing filter cake development (top), and sealing of concentrated leak (bottom). The filter seal results in a thin zone of soil with a slurry-like consistency and a permeability similar to that of the soils that eroded to form the seal (after Sherard, Dunnigan, and Talbot, 1984).

> seepage or leakage along the surface of the structure or through adjacent im pervious zones is the use of a properly designed filter and drainage zones around the conduit downstream of the impervious core along with quality constructed fill adjacent to the structure.
>
> Current policy is that cutoff collars should not be used as a seepage control measure and any other protruding features on a conduit should be avoided.

- *Natural Resources Conservation Service.*—From NRCS's *Earth Dams and Reservoirs* (1990, p. 6-7):

> Use a filter and drainage diaphragm around any structure that extends through the embankment to the downstream slope. . . . It is good practice to tie these diaphragms into the other drainage systems in the embankment or foundation. Foundation trench drains and/or embankment chimney drains that meet the minimum size and location limits are sufficient and no separate diaphragm is needed.

- *U.S. Army Corps of Engineers.*—From USACE's *General Design and Construction Considerations for Earth and Rock-Fill Dams*— (2004a, p. 6-6):

> When conduits are laid in excavated trenches in soil foundations, concrete seepage collars should not be provided solely for the purpose of increasing seepage resistance since their presence often results in poorly compacted backfill around the conduit. Collars should only be included as necessary for coupling of pipe sections or to accommodate differential movement on yielding foundations.
>
> . . . Drainage layers should be provided around the conduit in the downstream zone of embankments without pervious shells. . . . In embankments having a random or an impervious downstream shell, horizontal drainage layers should be placed along the sides and over the top of conduits downstream of the impervious core.

Filter zones are provided in embankment dam designs to meet various requirements and conditions. Filters serve the following purposes (ASDSO, 2003):

- For water seeping through the natural voids of the soil (embankment dam or foundation), a drainage system is designed to intercept this seepage and carry it to a safe outlet.
- A filter consists of a graded sand and/or gravel material designed to prevent the migration of soil particles from the base soil being drained.
- The filter supports the soil discharge face, and no movement of soil occurs with water flow.

- Filters are placed next to the soil. If needed, one or more coarser zones are placed behind the filter to serve as the drain. Collection pipes may be used to carry the water to a safe outlet.

- If the filter has sufficient permeability, it can serve as both the drain and the filter.

- Filters also intercept cracks, openings, or other anomalies where water flow has the potential to develop a concentrated leak.

- In cracks or openings, filters intercept soil moving in suspension with the water; a filter cake is formed that seals the crack and prevents further erosion.

FEMA is sponsoring the development of a "best practices" guidance document for filters used in embankment dams. This document will contain detailed procedures and guidelines for design and construction of filters. The design manual will be based on experience provided from experts in the fields of geotechnical engineering and construction. The expected publication date is 2007.

Filters used in conjunction with conduits through embankment dams generally fall into three broad categories: chimney filters, filter diaphragms, and filter collars. These filters are discussed in the following sections.

6.3 Chimney filters

A chimney filter that extends upward to the highest probable pool level and extends across the length of the embankment from abutment to abutment is a common element for most high and significant hazard embankment dams. Chimney drains are also valuable for sites with a high permanent water storage level, because they intercept and lower the phreatic line and maintain a stronger downstream zone of unsaturated soil. Figure 87 shows a double gradation zone chimney filter being installed in the construction of a modern embankment dam.

Chimney filter zones are a valuable protection against internal erosion in transverse cracks that could occur in the embankment dam. Chimney filters are also commonly used when embankment dams contain zones of widely varying gradation. The chimney filter provides a transition and filtering capability between these zones. Multiple filter and drain zones may be required in embankment dams that include zones of soils with a wider range in gradation. Examples are embankment dams with zones of impervious, finer grained soils with coarse shell zones of rock or gravel fill.

Figure 87.—Two stage chimney filter within an embankment dam located in Texas.

Embankment dams with chimney filters do not normally require a separate feature to control internal erosion or backward erosion piping along the conduit. The chimney filter will usually encompass the conduit and serve the function of a filter diaphragm as well as the other primary functions of a chimney filter, such as providing transition filter capability and controlling the phreatic line. Figure 88 (top) shows a zoned embankment dam with a chimney filter constructed along the interface between the central core of the dam and the downstream shell. The chimney filter encompasses the conduit at the intersection and serves as a filter diaphragm as well as a chimney filter.

Figure 88 (bottom) illustrates a design where an embankment chimney filter also serves as a filter diaphragm around the conduit. This example is for a homogeneous embankment with a vertical chimney filter. Chimney filters are typically installed in new construction or within embankment dams undergoing extensive renovation.

Figure 89 provides another example of a typical design used for a high hazard embankment dam. This design includes a chimney filter, a drain at the downstream edge of the cutoff trench, and a foundation blanket drain. The chimney filter and cutoff drain satisfy the functions of a filter diaphragm around the conduit. The blanket drain serves as an outlet for the collected seepage flow. The design shown is typical for embankment dams that have distinctly different materials in the core zone and the exterior shells of the dam. The foundation blanket drain may also function to collect seepage in bedrock or permeable foundation horizons, and function to convey collected seepage to the downstream toe. Not all high hazard embankment

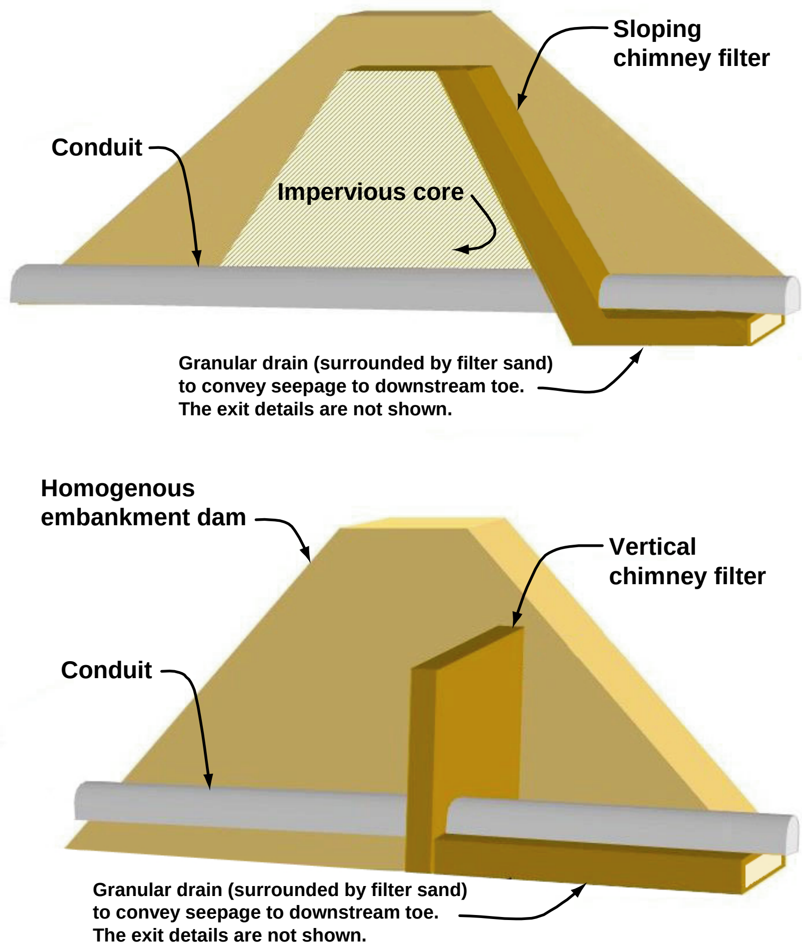


Figure 88.—Typical configurations for chimney filters used in the design of embankments with conduit penetration. A chimney filter may be constructed either on a slope (top) or with a vertical configuration (bottom) within the embankment dam.

dams require the same configuration of foundation drainage features shown in figure 89, but the design shown is a typical one.

Some low hazard embankment dams may not include a chimney filter for the entire length of the dam, if the following factors are present:

- The embankment dam is constructed of soil(s) with a good resistance to both internal erosion and backward erosion piping. Particularly important is that dispersive clays are not used in the construction.

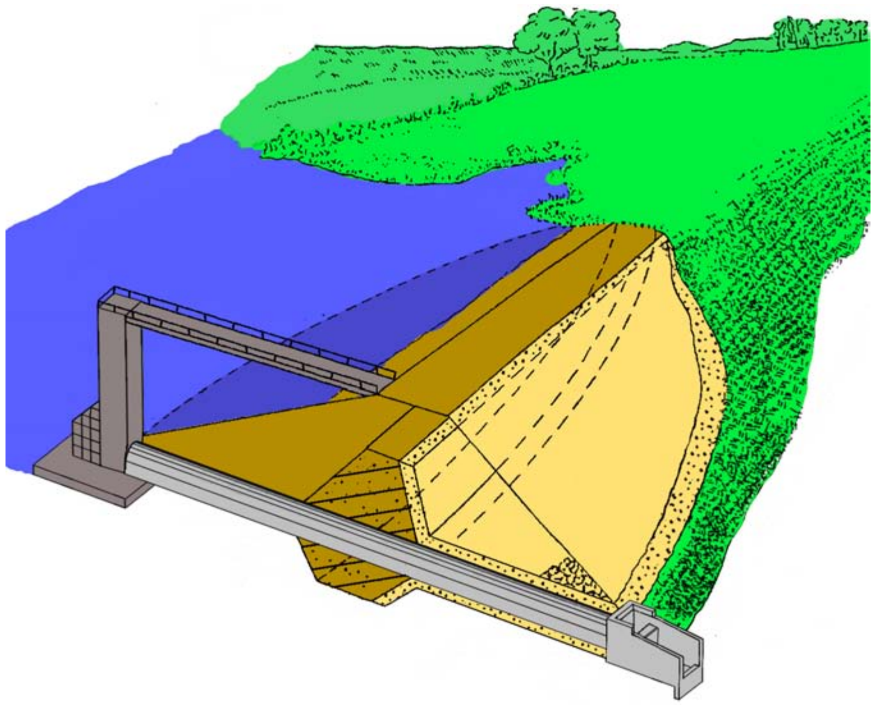


Figure 89.—Typical design used for embankment dams with distinctly different materials in the core zone and exterior shells of the dam.

- Zones of widely varying grain size are not used adjacent to one another in the cross section. Examples include core zones of fine grained soil with exterior zones of coarser gravel or rockfill.

- Abrupt changes in the cross section transverse to the centerline are not present. Examples are bedrock ledges, closure sections, and excavated trenches.

- Good oversight of construction is provided, including quality assurance and control that are consistent and effective.

- Special care is taken in following recommendations for compaction of fill surrounding the conduit, as discussed in section 5.3.2.

If a chimney drain is not included in the design of a low hazard embankment dam, the design measures for preventing internal erosion or backward erosion piping along the conduit may consist of three basic choices:

1. A filter diaphragm is a valuable defensive design measure even for low hazard classification embankment dams with favorable site conditions. The filter diaphragm will intercept flow along discontinuities along the pipe or through

cracks in the earthfill immediately surrounding the conduit that are caused by differential settlement associated with the conduit. Cracks in the earthfill surrounding the conduit may also be caused by desiccation during interruptions of fill placement, hydraulic fracture, and other mechanisms discussed in this document. Section 6.4 discuss filter diaphragm considerations in detail.

2. A filter collar is sometimes used rather than a filter diaphragm. This configuration protects against flow directly along a conduit, but does not address potential flow in cracks that may occur in the soils surrounding the conduit. Section 6.5 discusses in more detail the guidelines for using a filter collar rather than a filter diaphragm.

3. Some design agencies, including the NRCS, still allow the use of antiseep collars as a defensive design measure to address flow along conduits for low hazard embankment dams with favorable soil and site conditions. Some regulations by State and other entities may also require the use of antiseep collars. As discussed in detail in appendix A, the theory behind the development of antiseep collars is flawed, and their continued use may be considered a relic of conventional design. Because antiseep collars impede the uniform compaction of backfill along the conduit, and their theoretical basis is not sound, their use has been largely abandoned. The only likely benefit of antiseep collars would be an interruption of flow that might occur from poor construction practices on circular conduits where the pipe is dislodged by construction efforts or backfill under the haunches of the pipe is loose. However, antiseep collars are not recommended as the "best practice" approach to the design of conduits.

6.4 Filter diaphragms

A filter diaphragm is an important component of design for both new construction and the renovation of older embankment dams. Some low hazard embankment dams constructed of soils that are inherently resistant to internal erosion or backward erosion piping may not include a chimney filter zone for the entire length of the dam. However, these embankment dams should still contain a filter diaphragm around any conduits within the dam.

As discussed in section 6.3, chimney filters are used in many embankment dam designs, both new and renovation. The chimney filter zone can usually satisfy the function of a filter diaphragm. A separate component is not required for those embankment dams, if the chimney filter surrounds the conduit in a similar fashion as the filter diaphragm would.

A filter diaphragm (figures 90 and 91) is a designed zone of filter material constructed around a conduit in which a chimney filter is not being used (usually in

Figure 90.—Construction of a filter diaphragm within an embankment dam.

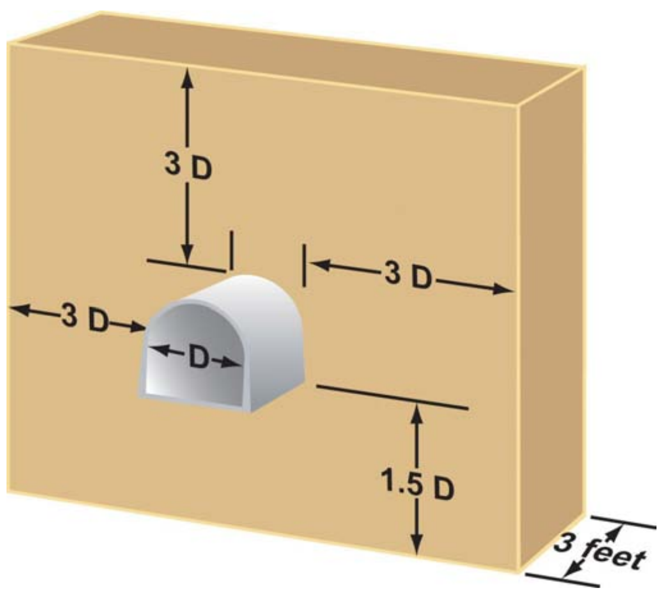


Figure 91.—Typical configuration for filter diaphragm used in the design of an embankment dam.

the renovation of an existing embankment dam). This zone can act both as a drain to carry off water and as a filter to intercept soil particles being transported by the water. The filter diaphragm will intercept both intergranular flow through the embankment dam and flow through cracks in the earthfill or along the interface between the conduit and the earthfill. Any fines being eroded from the embankment will be filtered by the diaphragm of sand that surrounds the conduit. The fines carried by the flowing water will accumulate on the surface of the diaphragm and develop a filter cake. The filter cake that develops on the upstream face of the filter diaphragm reduces the flow and prevents further erosion of any cracks caused by this flow. The filter diaphragm must extend far enough from the conduit that it can intercept all potential water flow paths associated with the conduit. A filter diaphragm is typically installed during new construction or with conduit renovations.

If the only postulated flow path is immediately along the contact between the earthfill and the conduit, the filter diaphragm may not need to extend far from the conduit. As an example, some agencies only use a filter diaphragm 18 inches thick, which is similar to a filter collar. In other cases, the embankment dam may be subject to hydraulic fracture in zones that are far above and on either side of the conduit. In the absence of a chimney filter, the filter diaphragm may need to be much wider and taller than the dimensions of the conduit to intercept those cracks.

A filter diaphragm that extends farther from the conduit is often recommended for designs where significant differential settlement is associated with the conduit and/or the trench used to install the conduit. This type of filter diaphragm is often used for embankment dams constructed without a chimney filter, when soils with a very low resistance to internal erosion, such as dispersive clays, are used to construct the dam. This type of diaphragm is a zone of designed gradation filter sand that completely encircles the conduit. The shape of the filter diaphragm is usually either rectangular or trapezoidal, and the diaphragm is typically 3 feet thick. Figure 91 shows a typical configuration for a filter diaphragm. For further guidance on recommended dimensions for a filter diaphragm, see NRCS's *Earth Dams and Reservoirs* (1990) and *Dimensioning of Filter Drainage Diaphrams for Conduits According to TR60* (1989).

The NRCS filter diaphragm typically has the following characteristics. Agency policy and the judgment of the individual designer may dictate different dimensions:

- *Configuration*.—The filter diaphragm is a rectangular or trapezoidally shaped zone of filter sand that is about 3 feet wide in a direction perpendicular to the conduit; see figure 91.

- *Location*.—Locating the filter diaphragm along a conduit depends on several site conditions. If the embankment is zoned, the filter is often located at the juncture of the impervious core zone and downstream shell zone. In a homogeneous embankment dam, the location of the filter diaphragm is usually based on the following requirements:

    1. Downstream of the cutoff trench.

    2. Downstream of the centerline of the embankment dam when no cutoff trench is used.

3. Upstream of a point where the top of the filter diaphragm has at least a thickness of soil overlying it that is a minimum of one-half of the difference in elevation between the top of the diaphragm and the maximum potential reservoir water level.

The rationale for the third requirement is that if an open crack occurred within the embankment dam and the full reservoir water pressure was acting on the crack, that pressure would be transmitted along the crack with little head loss to the point where the crack intercepted the filter diaphragm. At that point, the crack would presumably be sealed from sloughed particles carried along the crack to the face of the filter diaphragm. Then, at that interface between the open crack with a seal and the filter diaphragm (see figure 86 [bottom]), full reservoir hydrostatic pressure could exist. The criterion is intended then to ensure that the weight of overlying soil in the embankment counters this hydrostatic pressure. The rule requiring the thickness of one-half the reservoir head is based on the simplification that the unit weight of moist earthfill is approximately twice the unit weight of water.

- *Vertical/horizontal limits.*—The filter diaphragm should extend below and to either side of the conduit far enough to intercept potential flow along excavation/embankment interfaces. Usually, the filter diaphragm extends into the foundation a dimension equal to at least 1.5 times the diameter of the conduit, unless bedrock is encountered at a shallower depth.

- *Lateral limits.*—The filter diaphragm usually extends laterally a distance at least equal to 3 times the diameter of the conduit or a minimum of 10 feet from the sides of the conduit. In some situations the filter diaphragm may need to be wider than these minimum suggested dimensions. For instance, if an excavation has been made for the conduit, the filter diaphragm should notch into the excavation slopes by at least 2 feet; see figure 92.

A designer should consider several factors in determining the dimensions to use for a filter diaphragm, as follows:

- *Whether a filter diaphragm is a "stand-alone" element of the embankment dam's design, or if it is a coincidental part of a chimney filter in the dam.*—Many embankment dams include a chimney filter that extends across the entire length of the dam. When the chimney filter is located where it can also encompass the conduit passing through the embankment dam, a separate filter diaphragm is not required. Figure 88 shows two configurations commonly used for chimney filters that would serve the function of a filter diaphragm, as well as the functions of a chimney filter.

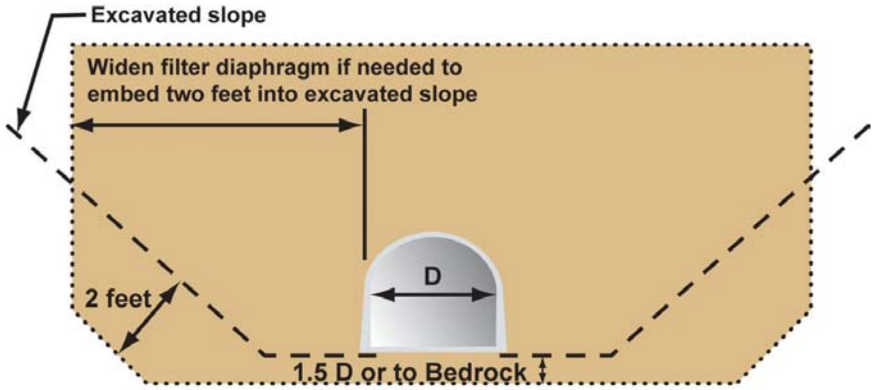


Figure 92.—Typical configuration for filter diaphragm used in design of an embankment dam. The filter diaphragm should extend into the foundation soils, where an excavation is made for the conduit.

- *The type of equipment used to construct the filter diaphragm*.—If a chimney filter is used in the design of the embankment dam and it serves the coincidental purpose of a filter diaphragm, then dimensions appropriate for a chimney filter should be used. Many times, chimney filters are sized for the width of equipment (about 10 to 12 feet) to accommodate production equipment in placing and compacting this zone in the embankment cross section. In small embankment dams where the cost of the chimney filter may be excessive, a narrower width may be considered.

- *The method of constructing the filter zone*.—If the chimney filter zone or filter diaphragm is constructed concurrently with the adjoining fill zones, using a width of 10 to 12 feet is suited to most construction equipment. A chimney filter designed with multiple filter zones complicates construction. Figure 87 shows such a design. If the filter zone is placed in a trench cut in compacted fill, a width of 3 feet is often specified, because that is typically the width of backhoe buckets used for this method of construction. A paper by Hammer (2003) includes good discussions of the advantages and disadvantages of various methods for constructing chimney filter zones. The discussions would apply equally well to sites where only a filter diaphragm was used instead of a full chimney filter section. The trenching method is illustrated in figures 6, 7, and 8 of that paper.

- *The predicted zones of embankment susceptible to hydraulic fracture resulting from the presence of the conduit in the fill*.—The filter diaphragm should extend vertically and laterally far enough to intercept all zones of the fill and foundation that are susceptible to hydraulic fracture attributable to the presence of the conduit in the dam. Hydraulic fracture is discussed in section 5.2. Hydraulic fracture zones not caused by the conduit, but by other factors, such as steeply dipping bedrock surfaces, are usually addressed with chimney filter zones in addition to a filter diaphragm.

- *The ability of the filter diaphragm to prevent propagation of a crack through the zone.*—The purpose of a filter diaphragm is to intercept cracks in the earthfill and collect and filter any flow eroding the walls of the crack. The filter zone must be thick enough to prevent a crack from propagating through the filter. Many designers consider a thickness of 3 feet as adequate to satisfy this requirement. Other factors important in crack propagation include the gradation of the filter used for the diaphragm, its degree of compaction, and the potential for cementation of the filter. For less favorable conditions, wider filter diaphragms may be advisable.

Intergranular seepage passing through the filter diaphragm may be collected and conveyed downstream to the toe of the embankment dam with various design approaches. The outlet drain to convey the collected flow may be a combination of granular filters and it may or may not include a perforated collector pipe. Figure 93 shows one type of outlet drain for a filter diaphragm. This figure shows an outlet drain consisting of a zone of gravel surrounded by a fine sand filter, without a collector pipe. Collector pipes may also be included in the designs for outlet drains for filter diaphragms, particularly to provide a safety factor for conveying larger than expected flow quantities. Many designers contend that outlet drains should be designed to have a capacity to convey all of the collected flow in the granular zones alone, without considering the additional capacity provided by a collector pipe—the reason being that the collector pipe could eventually be damaged or otherwise become inoperative, and the granular zone would still be functional.

The estimated flow quantity that filter diaphragms are required to convey depends primarily on the predicted quantity of intergranular seepage, not flow through cracks that are intercepted by the diaphragm. If properly designed, the filter diaphragm will form a seal on the face of any intercepted cracks, and subsequent flow through the face of the crack at the filter will be similar to intergranular seepage.

In addition to the dimensions of filter diaphragms, designers must also decide whether to use a sloping zone or a vertical configuration for the diaphragm. Each configuration has advantages and disadvantages:

- *Sloping configuration.*—Filter diaphragms and chimney filters may also be constructed with a sloping configuration, as illustrated in figure 88 (top). This configuration is more common on larger embankment dams and those with distinct zones in the dam. The filter zone is often placed at the juncture between the core and shell zones in the dam as shown in figure 88 (top). This configuration reduces the effect of differential settlements between the filter zone and the adjacent embankment zones. Because sloping zones are typically

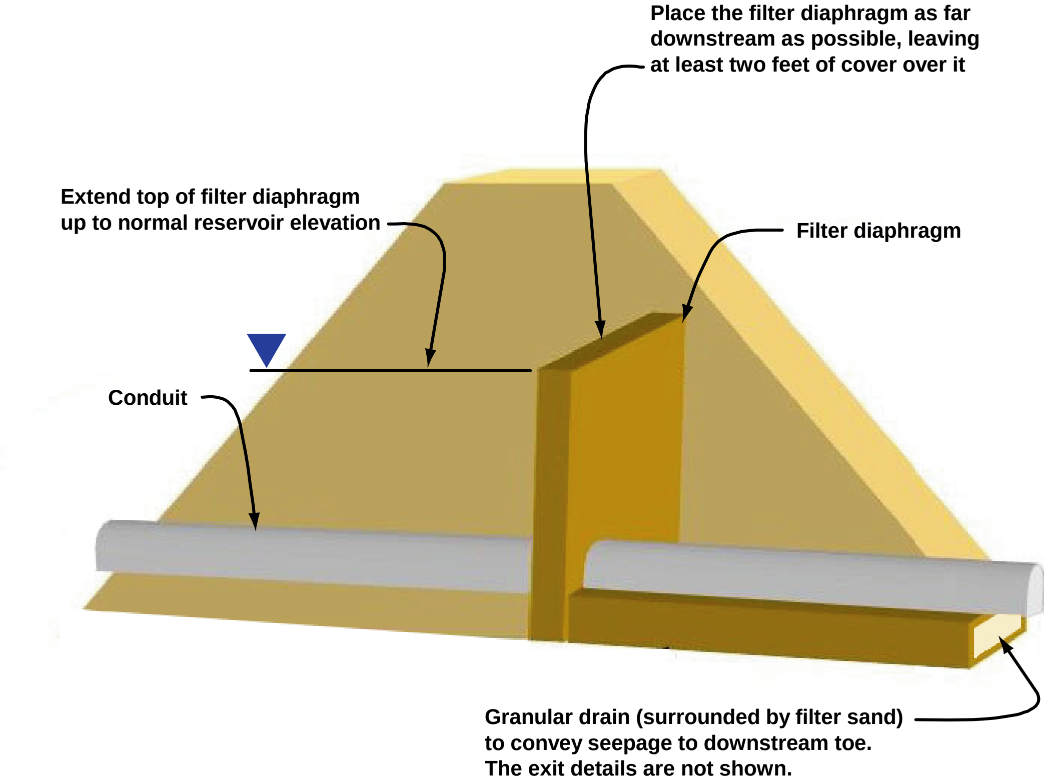


Figure 93.—Typical configuration for a filter diaphragm used in the design of an embankment dam. The figure shows the location of the filter diaphragm as far downstream as possible, leaving adequate cover over it.

wider than vertical zones, differential settlement occurs over a wider distance, also lessening the potential for cracking associated with the differential settlement. Collapse of the filter zone on wetting is still a concern, and proper compaction control is needed, as it is for a vertical zone. Sloping configuration zones have a lower potential to cause cracking of the surrounding embankment zones for reasons listed and are preferable when the design permits. Constructing a sloping filter diaphragm would be considerably more difficult for small homogeneous embankments, and this configuration is seldom used for those designs.

- *Vertical configuration*.—This configuration for a filter diaphragm is the one commonly used. Figure 88 (bottom) shows a vertical zone for the filter zone surrounding a conduit (In this case the zone is a combination filter diaphragm and chimney filter, but illustrates the shape for a design using a smaller filter diaphragm as well). Vertical filter diaphragms are commonly constructed using the trenching method, as shown in the paper by Hammer (2003). This shape of filter diaphragm is common in embankment dams that do not have distinct zones, and the engineering properties of the embankment soils on both sides of the diaphragm are similar.

Filter zones are typically composed of somewhat well graded relatively clean sand, such as ASTM C 33 fine concrete aggregate. The compressibility characteristics of this zone likely are different than those of the earthfill in which it is placed. This may create concern over differential settlement between the embankment soils and the filter diaphragm. A special concern is the potential for collapse of the filter zone upon wetting. To reduce this potential, filters are typically compacted to a moderate degree as described in section 6.8. Because any potential differential settlement is oriented parallel to the embankment, less concern occurs than if the differential movement were transverse to the embankment dam.

For an example of a project that used a filter diaphragm, see the case history in appendix B for Waterbury Dam.

6.5 Filter collars

A filter collar consists of a zone of filter material (usually sand) that completely surrounds a specified length of conduit. This type of filter is recommended, if the only flow that is considered likely is that along the contact between the conduit and the surrounding earthfill, and embankment soils are not dispersive clays.

A filter collar should be limited to sites with few problems. If conditions exist that could cause hydraulic fracture, or if soils in the embankment dam are very low in erosion resistance (such as dispersive clays), more substantial filter zones, as discussed in section 6.4, should be used rather than a filter collar. A filter collar is generally used in conduit renovation or new construction.

For renovations, the filter collar wraps the downstream one-third length of the conduit, and the filter is about 18 inches thick. The thickness depends upon design requirements. The USACE's *Design and Construction of Levees* (2000, p. 8-5) and *Culverts, Conduits, and Pipes* (1998a, p. 1-3) show a typical design. Figures 94 and 95 illustrate an example of this type of filter design for a conduit renovation.

The dimensions for the filter should vary with the size and complexity of the embankment dam. Larger filter collars and multiple zones may be needed for more complex, significant hazard to high hazard embankment dams or those with problematic soils. The gradation of the filter collar should be designed for filter compatibility with the surrounding soils in the embankment dam. At the downstream end of the filter collar, a zone of gravel may be placed at the end for

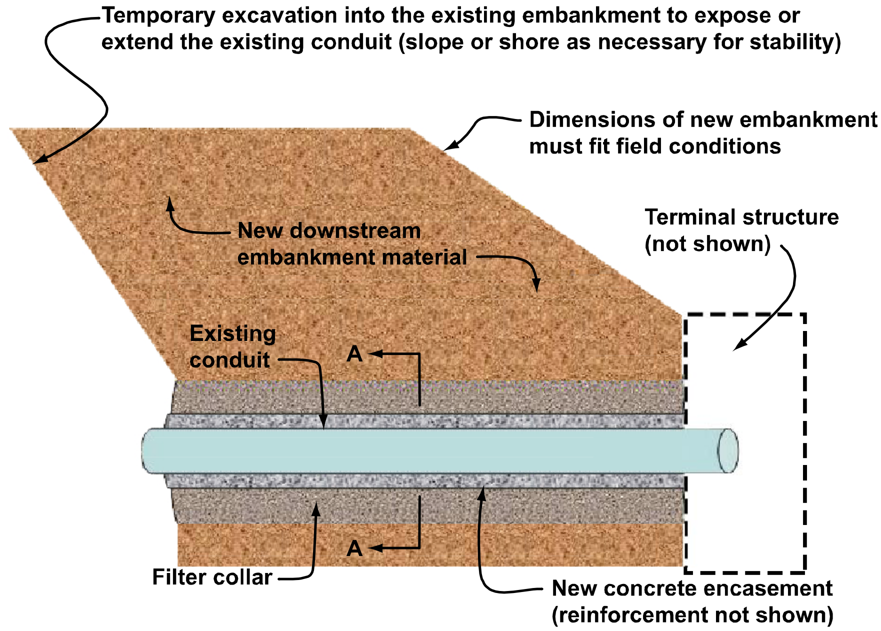
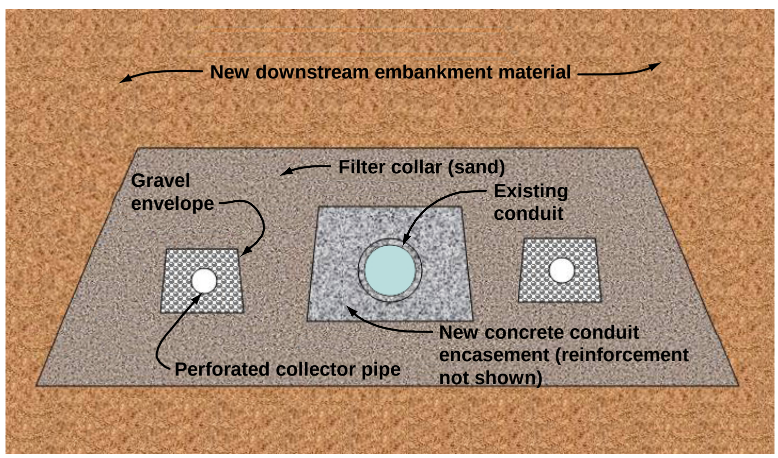


Figure 94.—Filter collar surrounding a conduit renovation.



Section A-A

Figure 95.—Cross section showing a filter collar surrounding a conduit renovation. The drain pipes located on both sides of the conduit collect and convey any seepage within the filter collar to a downstream exit location.

filtering the sand and providing a controlled outlet for the collected seepage. The gravel should meet filter criteria for the sand filter.

At the very downstream toe of the embankment dam, a short section of perforated drain pipe (similar to a toe drain) is often provided to collect and convey any seepage water out of the filter collar. This collector pipe will help keep the toe area from becoming boggy. The pipe will also provide opportunity to measure seepage flow and monitor for sediment transport. Provisions should be made in the design of the collector pipe to allow for inspection by CCTV equipment. See section 9.5.4.4 for a discussion of CCTV inspection.

Burying the collector pipe too far into the embankment should be avoided. The gravel envelope drain should be capable of providing the needed drainage. The designer should provide access provisions for the collector pipe to enable inspection and cleaning. Also, should the collector pipe become damaged, it should be located such that it can be removed and replaced.

6.6 Filter and drain gradation design

Designing the gradation of the sands used in the filter is important if they are to function properly. Standard filter design methods, such as the NRCS design procedure shown in *Gradation Design of Sand and Gravel Filters*, National Engineering Handbook, Part 633, Chapter 26 (1994), the USACE's *General Design and Construction Considerations for Earth and Rock-Fll Dams* (2004a), and Reclamation's *Embankment Dams—Protective Filters* (1999) are typical. Materials suitable for filters will rarely be available onsite and are usually purchased from concrete aggregate suppliers or processed from materials near the site. For many designs, ASTM C 33 fine concrete aggregate is found to meet criteria. However, designers should always determine a range of compatible filter gradations that will protect the soils used in the surrounding embankment to increase construction flexibility. Sands used to construct filter diaphragms, filter collars, or chimney filters should be filter compatible with the embankment zones being protected, and they must also be able to deform and fill any cracks that may be propagated to the filter. If the filter does not have a property referred to as "self-healing," the crack could propagate through the filter, and the filter would not satisfy its intended function. Vaughan and Soares (1982, p. 29) and the USACE (1993, p. 8-6) have described a simple test for evaluating the self-healing ability of a filter. Factors that influence the ability of a filter to be self-healing are the percentage of fines (percent finer than the No. 200 sieve) and the plasticity of the fines. Filter designs usually require a low percentage of nonplastic fines (usually less than 5 percent as measured after placement in the embankment dam and compaction of the filter) to ensure that filters have adequate permeability and self-healing characteristics. Fine, poorly graded filters have less desirable self-healing characteristics than broadly graded, coarse filter materials. However, segregation of broadly graded filters can be a serious problem.

The no erosion filter test described by Sherard and Dunnigan (1989, pp. 927-930) is useful in evaluating whether a specific filter gradation is filter compatible with a specific base embankment soil. While existing filter criteria generally ensure filter compatibility, site-specific testing using the no erosion filter test is advisable for some situations. For high hazard embankment dams, where designers want additional documentation on the filter compatibility between a specific filter source and the embankment soils, or where designers wish to explore whether relaxing strict filter criteria would be safe, conducting laboratory filter tests with actual site materials is advisable.

Other considerations for the filter and drainage zone materials include:

- Granular materials should be hard and durable, so they will not break down during transportation, placement, and compaction. Overcompaction can reduce permeability and increase fines.

- The specified gradation should filter the embankment dam's core material and be permeable enough to avoid excess water pressure buildup.

- The filter gradation should be designed to avoid segregation during placement.

- A two-layer filter may be required for zoned embankment dams where the core and shell zones are very different.

- Designs for drainage zones favor permeability considerations over filtering criteria. Ordinarily, filters that are separate from the other embankment dam drainage zones are not expected to convey much flow, because their purpose is to intercept and prevent flow through cracks.

- The most likely damage that can occur to sand and gravel filter/drainage zones or material during construction is contamination or segregation.

- Segregation will occur when the filter or drain material is dumped from an end-dump truck or other hauling unit, where the material falls more than about 2 feet. Close inspection is always necessary to make sure segregation is not occurring. The use of narrowly graded materials helps to prevent this problem.

- Wide gradations (gradations that include a wide range of particle sizes) can be internally unstable. This is a problem when the finer portion of the filter can pass through the coarse portion with water flow; washing the finer portion out and leaving a very coarse soil matrix that will not serve as a filter for the base soil. This can be checked by mathematically dividing the grain-size curve into two gradations. If the coarse gradation does not meet the filter requirements for the fine gradation, the filter is internally unstable (ASDSO, 2003).

- Avoid placement of filter materials in freezing temperatures. Frozen filter material cannot be properly compacted.

Recently, an additional method has been proposed that expands on the existing research on protective filters. The method (Foster and Fell, 2001, pp. 398-407) establishes a "continuing erosion boundary" that is based on the analysis of the results of laboratory tests and the characteristics of dams that have experienced internal erosion incidents. The method can be used to determine whether filters that are coarser than required by modern filter criteria will eventually seal, or experience continuing erosion leading to possible failure of the embankment dam in the event that internal erosion begins. The method is intended to help evaluate filters in existing embankment dams only and should not be used to design new filters for dams.

6.7 Construction of the filter

Construction of the filter should be performed carefully to ensure that high quality is obtained. The construction needs to ensure that the filter is placed completely around the conduit. Sloppy placement techniques can result in voids in the filter or inadequate bond with the conduit encasement.

Placement of the sand filter and adjacent materials in the embankment must be performed to avoid contamination of the filter. During construction, the sand filter zone should be maintained above adjacent materials to preclude contamination. Construction traffic crossings over filter zones should be minimized. The surface of the filter at the crossing can be covered with plastic and the plastic covered with earthfill to reduce contamination at the crossing.

Placement techniques should ensure that segregation of the filter does not occur. Segregation will cause portions of the filter to be overly coarse, which can allow embankment material to flow through, negating the purpose of the filter. Segregation can be avoided by careful selection of the handling equipment. The following has been adapted from Reclamation's *Embankment Dams—Protective Filters* (1999, p. 16).

> A common cause of segregation is the manner in which material is handled. Material placed in a pile off a conveyor, or loaded from a chute, or from a hopper segregates because the larger particles roll to the side of stockpiles or piles within the hauling unit. Material dumped from a truck, from loader, or other placing equipment will almost always segregate, with the severity of the segregation corresponding to the height of the drop. When material is dumped on the fill, segregation occurs.

> Segregation can be minimized in several ways. First, the designer should avoid using widely graded filters that are more prone to segregation. Rather than using a single, widely graded filter, a designer could specify a dual band of filters. A fine filter layer to protect the finer embankment materials would be outletted into a coarser layer used to outlet the collected flow. Secondly, construction techniques to control segregation should be specified and enforced. Use of rock ladder, spreader boxes, and tremies or "elephant trunks" for loading hauling units, and hand working the placed materials will help prevent segregation. If material is dumped, limiting the height of drop will help. Often the height of drop is limited to 4 feet maximum. Placing filter/drain material with belly dumps is a better method than others because the height of drop of materials is limited by the equipment. Limiting the width of the belly dump opening by chaining or other means can increase their ability to limit segregation. Using baffles in spreader boxes and other placing equipment can help reduce segregation. The personnel inspecting the filter/drain production, placement, and compaction should be trained in the techniques effective in preventing segregation. They should be aware of contract provisions in specifications that are intended to prevent segregation and be prepared to enforce those specifications.

Filter zones must be compacted properly to avoid problems. Vibratory compactors (usually smooth drum or plate), are more efficient in densifying filters than "kneading" compactors (such as sheepsfoot or padfoot), without causing much breakdown. Breakdown of the filter material's particles can cause the gradation of filters to change. The most harmful result of breakdown is the increase in the percentage of fines (usually defined as the material passing the No. 200 sieve size). Excessive fines in the material will drastically reduce the material's permeability and adversely affect other of the filter's attributes. Overcompaction should be avoided. Often the gradation of the filter is specified as "in-place, after compaction," thus ensuring that the intended gradation is obtained. Also, specifying filter material that is comprised of hard and durable particles is important in helping minimize breakdown.

Previous sections have discussed factors that can affect the integrity and quality of the filter diaphragm or collar around a conduit. A paper by Hammer (2003) contains valuable additional guidance on constructing drain zones within embankment dams. Recommendations in that paper include other factors in addition to those discussed in previous sections of this document. Recommendations are included for methods to avoid contamination of filter zones, advantages and disadvantages of various schemes for constructing vertical drainage zones, and others. The recommendations in that paper should also be considered when constructing filter collars and diaphragms associated with conduits, as well as when constructing other types of embankment drainage zones.

6.8 Specifications and density quality control and quality assurance for filters and drains

Contract specifications contain requirements for compacting sand for filters. Quality control personnel are responsible for ensuring that the specifications are met. Quality assurance personnel then ensure that the quality control methods and equipment are satisfactory.

Filters are compacted using two principal types of specifications. Compaction of sands is important for filter construction. Controlled compaction of the filter sands is important to prevent settlement of the sands on wetting and liquefaction during seismic activity. At the same time, filters should not be overly compacted because that can reduce their ability to "self-heal" or adjust to any movements in the underlying embankment and foundation. The two types of specifications used for controlling compaction of sands and gravels are:

- *Method placement specification*.—A method placement specification requires the filter sand to be compacted in lifts of a stated maximum thickness using specified equipment operated in a specified manner. The specification assumes that the designer has previous favorable experience with a specified method and feels sure that the filter sand will have adequate properties, if it is compacted using these procedures. This type of specification does not require a specific density or water content, but relies on the specified procedure to produce desirable filter.

  Quality control and quality assurance for this type of specification concentrate on observations and documentation of the processes used to place the filter, compared to the acceptable methods listed in the specifications.

  An example of a method placement specification is shown in the NRCS's *Drainfill*, National Engineering Handbook, Part 642, Specification No. 24 (2001f, p. 24-2). Class I compaction requires each layer of drainfill to be compacted "... by a minimum of two passes over the entire surface with a steel-drum vibrating roller weighing at least 5 tons and exerting a vertical vibrating force of not less than 20,000 pounds at a minimum frequency of 1,200 times per minute, or by an approved equivalent method."

  For filters, using smaller compaction equipment, such as walk-behind vibratory rollers and plate compactors, may be required if working space is limited.

  Test fills can be performed in advance of construction to check on the adequacy of method type placements.

Construction specifications typically also include other requirements. Examples from the NRCS's *Drainfill*, National Engineering Handbook, Part 642, Specification No. 24 (2001f, p. 24-1) include:

> Drainfill shall be placed uniformly in layers not to exceed 12 inches thick before compaction. When compaction is accomplished by manually controlled equipment, the layers shall not exceed 8 inches thick. The material shall be placed to avoid segregation of particle sizes and to ensure the continuity and integrity of all zones. No foreign material shall be allowed to become intermixed with or otherwise contaminate the drainfill.
>
> Traffic shall not be permitted to cross over drains at random. Equipment cross-overs shall be maintained, and the number and location of such crossovers shall be established and approved before the beginning of drainfill placement. Each crossover shall be cleaned of all contaminating material and shall be inspected and approved by the engineer before the placement of additional drainfill material.
>
> Any damage to the foundation surface or the trench sides or bottom occurring during placement of drainfill shall be repaired before drainfill placement is continued.
>
> The upper surface of drainfill constructed concurrently with adjacent zones of earthfill shall be maintained at a minimum elevation of 1 foot above the upper surface of adjacent earthfill.
>
> When placed, drainfill shall be in a wet or near saturated condition. Each layer of drainfill shall be saturated immediately prior to compaction.
>
> Drainfill shall be placed in such a manner as to prevent segregation of particle sizes.

Application of water in front of the vibratory roller drum during compaction is crucial. The inability to achieve the desired density is typically due to insufficient water application.

- *End result specification*.—An end result specification requires the filter sand to be compacted to a specified value of dry density. Usually, the required density is specified by reference to a standard test. The traditional method for specifying filter sand compaction uses relative density terminology and tests. ASTM D 4254 describes the test used to measure the minimum index density of a filter sand; ASTM D 4253 describes the test for maximum index density of a sand. NRCS's *Drainfill*, National Engineering Handbook, Part 642, Specification No. 24 (2001f, p. 24-2) shows an example of an end result specification. Class A compaction requires each layer of drainfill to be compacted ". . . to a relative density of not less than 70 percent as determined by ASTM D 4254."

Various degrees of compaction have been historically used. Relative density specifications have typically required placement to relative density values in the range of 50 to 85 percent. Values for specified relative density may be as low as 50 percent for low hazard projects, to as high as 85 percent for larger drain zones in high hazard projects. Relative density specification may not be practical for small projects, because the equipment needed to perform the tests for index density are not readily available for field use.

An alternative to using relative density tests is a special type of Standard Proctor (ASTM D 698) compaction test. Research (McCook, 1996) has shown that good correlations exist between relative density test values for filter sands and a dry density value obtained using dry sand in a ASTM D 698 mold. The one-point test uses the ASTM D 698 (Method A) energy (25 blows per lift of a 5.5-pound hammer dropped 12 inches, using 3 lifts to fill the mold). For many sands, 70-percent relative density corresponds to the dry density obtained in the special ASTM D 698 test on dry sand. A value of 50 percent relative density correlates with 95 percent of the dry density obtained in the special ASTM D 698 test. An example of a specification using this alternative is NRCS's *Drainfill*, National Engineering Handbook, Part 642, Specification No. 24 (2001f, p. 24-2) :

> The compacted density shall be greater than 95 percent of the maximum dry density as determined by the method in ASTM D 698. The ASTM test procedure D 698 shall be modified to consist of a 1-point test performed on a representative sample of oven-dried drainfill.

When an end result type of specification is used to control the placement of filters in drainage and filter zones, such as a filter diaphragm, quality control testing is required to verify that the placed sand meets the specified requirements. Accuracy of the quality control testing is essential to prevent misunderstanding of the in-place density. Quality control tests that underestimate in-place density will lead to additional compaction in order to achieve the specified density. This additional compaction can lead to additional breakdown of the filter material. Quality control tests of compacted sands are performed most frequently using one of the following two methods:

- *Sand cone method*.—ASTM D 1556.

- *Nuclear gauge method*.—ASTM D 2922. Note that a separate ASTM Standard Test Method applies to measuring the water content by the nuclear gauge, ASTM D 3017. The ASTM Standard Test Methods for performing nuclear gauge measurements of dry unit weight and water content are being revised. The proposed revision will combine the two test methods into a single ASTM Standard Test Method. At the time of the writing of this guidance document, an ASTM Standard Test Method number had not been assigned for the revised standard.

The sand cone method is a direct measurement of in-place density (weight of solids, wet of water, and volume), whereas the nuclear method is an indirect measurement technique (measurement of backscatter radiation from a prescribed source). By definition, indirect measurement techniques require some form of conversion or empirical relationship. Knowledge and use of these relationships should be well understood by the user to guard against drawing incorrect conclusions on the nature of the material being tested.

To obtain accurate results, these tests must be performed carefully with all the precautions listed in the ASTM Test Methods carefully followed. Nuclear tests that are performed in a trench condition require that corrections to the measurements be made according to the gauge manufacturer's recommendations. Because the nuclear gauge measures water content indirectly by counting hydrogen ions, water content measurements must also be corrected by comparing readings to the oven-dry method (ASTM D 2216).

Careful calibration of the sand used in the sand cone method is important to obtaining reliable results. Experienced personnel are essential to obtain reliable results for both tests. The reader is cautioned on two points. First, opinions differ on the acceptability of the test procedures described above. Second, this discussion is only relevant to uniformly graded sand material (filter material). This section does not apply to other soil types, such as broadly graded material containing cobbles.

6.9 Use of geotextiles

Due to the lack of long term performance information on the use of geotextiles in embankment dams, it is current practice that they are not used in locations that are both critical to dam safety and inaccessible for repair. The use of geotextiles can be considered in some cases that may be critical to dam safety, but the geotextiles must be accessible for replacement. The designer must assess the potential hazard posed by failure of the geotextile and the time available to respond and repair or replacement the geotextile (France, 2000, p. 2-5).

Some limitations to evaluate when considering the use of geotextiles (ASDSO, 2003):

- As with any filter, a geotextile will clog when water containing soil in suspension enters the filter face.

- For preventing development of a concentrated leak in a crack or opening in the embankment dam, it is desirable for the filter face to clog in the area of the crack. Other areas should remain open so normal seepage through pores of the soil can be intercepted and safely discharged through the drainage system.

- Properly designed sand filters support the soil discharge face and prevent the movement of fines that would clog the filter.

- Geotextiles by themselves do not support the soil discharge face as a granular filter does.

- Geotextile installation must be made in such a way that the geotextile has intimate contact with the soil discharge face, with the distance between contact points being similar to a granular filter; if not, soil movement will occur and clog the geotextile.

- A coarse granular fill or a geocomposite on the downstream side of the geotextile generally does not provide the needed uniform pressure on the geotextile to provide the needed support to the soil discharge face on the upstream side of the geotextile.

- Inside the embankment dam, geotextiles will have very large soil pressures on both sides of the geotextile that will hold it firmly in place with no chance to distribute stresses that are produced by differential movement within the soil mass along the plane of the geotextile.

- When a crack occurs in the embankment dam, it will likely tear the geotextile in the plane of the crack.

- Damage can occur during geotextile installation from equipment passing over it, from protrusions in the underlying material, or from moving sheets of the geotextile over a rough surface. The damage may not always be detectable.

- The structural integrity of the embankment dam depends on complete continuity of the filter drainage zone, and when constructed with a geotextile, it must be without holes, tears, or defects. This is difficult to achieve in a typical construction operation.

Chapter 7

Potential Failure Modes Associated with Conduits

Water flowing through conduits can escape through defects in the walls or between separated joints of the conduit. Soils can also be carried into a conduit through these defects. If a conduit is flowing under pressure and water is forced out of defects within the conduit, this can lead to a very serious problem that must be addressed by emergency action, since catastrophic embankment dam failure could result. If a conduit is not flowing under pressure, defects within the conduit may allow soils surrounding it to be carried into the conduit by seepage and hydraulic fracture. Water escaping through defects from within nonpressurized conduits will probably have a lower velocity and lower pressure and should be less damaging to the surrounding soils, than if the conduit were pressurized. This may allow for remedial measures to be undertaken in less of an emergency mode. Generally, defects in conduits are much more serious for conduits designed for pressure flow than for nonpressurized flow.

Attempting to place a filter on the outside of a conduit at a defect is likely to be ineffective, particularly for a pressurized conduit. The quantity of flow from the defect in a pressurized conduit will likely exceed the capacity of a filter designed to protect adjacent soils. In a nonpressurized conduit, the filter designed for a given size defect may be inadequate when the defect increases in size. Replacing or renovating conduits with defects are the only reliable long term solution to preventing damage to surrounding soils. See chapters 12 and 13 for guidance on replacement and renovation of conduits.

Water flowing through soils surrounding a conduit may also cause failure of the embankment dam. A conduit within an embankment dam is a discontinuity that may create stresses in surrounding soils that are conducive to hydraulic fracture. A conduit may impede uniform compaction of soils in its vicinity. The various ways embankment dams may fail (where conduits are the sole or primary contribution to the failure) are discussed in this chapter. Many other types of failure modes for embankment dams exist that are not associated with conduits and are outside the scope of this document.

The important factors that determine the timing and severity of problems related to soil movement associated with conduit defects include:

- *Type of material used in construction of the conduit.*—Some materials, such as corrugated metal, can corrode and develop defects much sooner than conduits constructed of more durable materials, such as concrete. Conduits overlain by high earthfills are more likely to be stressed beyond their strength, resulting in the development of cracks.

- *Dimensions of the crack or hole, in relation to the gradation of the surrounding backfill soil.*—Even small defects in conduits can result in movement of finely graded surrounding soils into the conduit.

- *Resistance of the surrounding backfill to internal erosion and backward erosion piping.*—Very fine sands and silts are extremely prone to particle movement from intergranular flow of water into defects in conduits. All soils will erode, if subjected to sufficient concentrated flow, such as might occur in cracks in the earthfill, but plastic clays and clayey coarse-grained soils that are not dispersive resist erosive forces better than silts and cohesionless coarse-grained soils.

- *Cracks in surrounding soil connected to water sources.*—If cracks in surrounding soil connect to water sources, erosion of the crack walls can increase dramatically and lead to catastrophic failure of the embankment dam. This can occur for erosion of materials into the conduit or along the conduit.

- *Existence of differential head.*—The potential for internal erosion or backward erosion piping is directly related to the differential head causing the flow of water, whether the flow is intergranular seepage or flow through cracks in the soil. High gradients increase the likelihood of internal erosion or backward erosion piping. Even if the head in the reservoir is not high, continued flow through cracks in the soil surrounding the conduit is likely to result in excessive erosion of the soil.

- *Type of flow.*—Conduits flowing under pressure are more likely to develop problems associated with conduit defects than nonpressurized conduits. The consequences of the problems that develop related to defects will be greater in pressurized conduits than those associated with defects in conduits that are not pressurized.

- *Backfill able to support a tunnel.*—Water escaping from defects in a conduit may erode surrounding soils. The ability of the soils to support a tunnel will determine the type of problem that develops. Backward erosion piping requires soil to be present that can support a tunnel feature. Otherwise, sinkholes or other types of features may be more likely to be the expression of the erosion.

There are four main potential failure modes involving conduits through embankment dams. These failure modes are discussed in the following sections.

7.1 Failure Mode No. 1: Backward erosion piping or internal erosion of soils into a nonpressurized conduit

For this failure mode, the conduit is surrounded over at least part of its length by soil with a low resistance to backward erosion piping. If the conduit develops a defect from deterioration, or a joint in the conduit becomes open from movement and seepage is occurring through the surrounding embankment, seepage forces may carry soil particles into the conduit. For this failure mode, the conduit is presumed to have an interior pressure lower than the seepage pressures in the surrounding soil. Figures 96, 97, and 98 show conduits with defects where water is entering the conduit. In figures 96 and 97, the defects are separated joints in a conduit. In figure 98, the defect is a poorly constructed joint in a CMP.

If the soil surrounding the conduit defect is resistant to backward erosion piping and the defect in the conduit is small, the time for serious erosion of surrounding soils to develop could be lengthy. Inspections of the conduit should disclose the presence of defects and allow for timely repair before serious problems develop. However, if the reservoir head is high and the defect in the conduit is large enough, the potential for either backward erosion piping or internal erosion is significant. Backward erosion

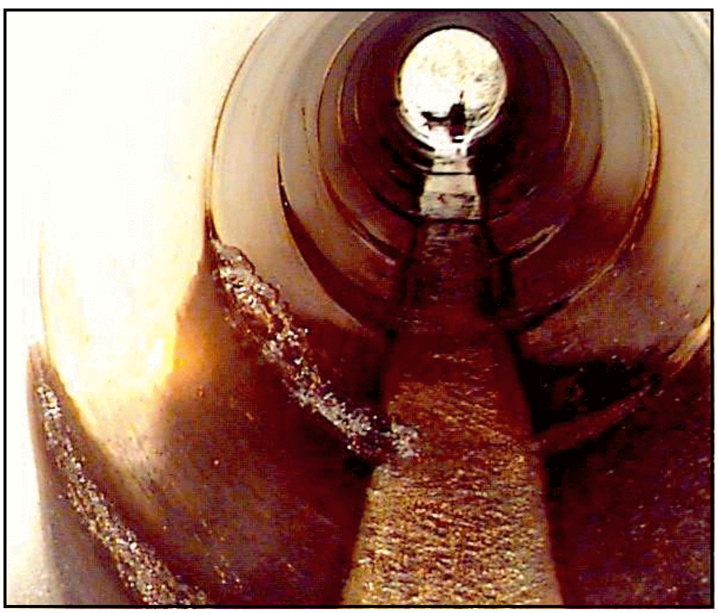


Figure 96.—Leaking joints in a 60-inch diameter RCP spillway. Several large voids were also observed in the adjacent earthfill on the upstream slope.

Figure 97.—Soil particles being carried into an outlet works conduit through a joint.

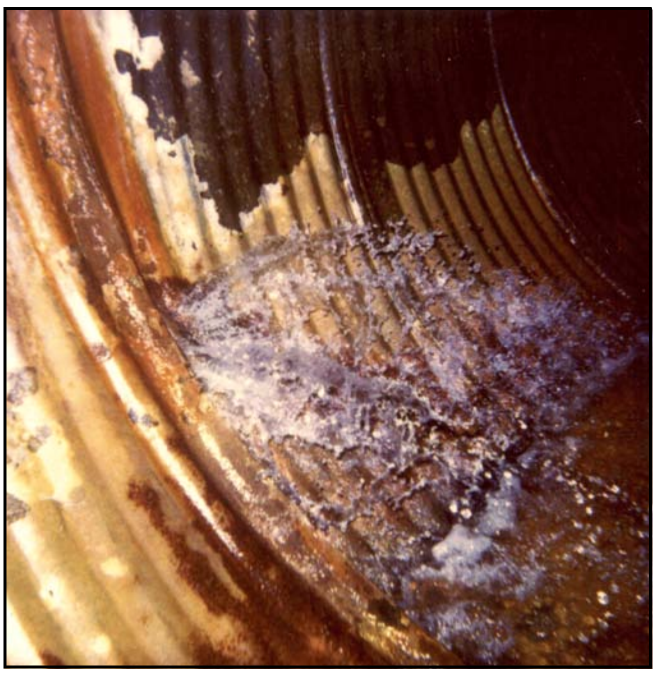


Figure 98.—Leakage from an unauthorized "field joint" constructed by the contractor about 5 feet downstream from the spillway riser structure. An inspection revealed that nearly all of the joints were exhibiting severe leakage and loss of embankment material.

piping could occur from seepage forces surrounding the defect in the conduit if the soils are susceptible. If the defect is large enough and the reservoir head is high enough, the loss of particles from the surrounding soil body caused by backward erosion piping could be severe.

Internal erosion could occur if a preferential flow path (like a hydraulic fracture) develops that is connected to the conduit defect. If internal erosion occurs in soils surrounding a conduit defect in this failure mode, the potential for eventual failure is high, because all soils when subjected to continued flow along a preferential flow path are erosive over time. Highly erodible soils, such as nonplastic silts, broadly graded silty coarse-grained soils, and dispersive clays, could develop erosion features more quickly. The most likely manifestation of erosion in this failure mode is a sinkhole that develops on the embankment surface.

As previously discussed, Failure Mode No. 1 may involve either a backward erosion piping or internal erosion mechanism of particle erosion. The *Introduction* of this document includes extensive discussions of factors that should be evaluated to determine which of these mechanisms is likely for a specific situation.

The sequence in which this failure mode could develop is illustrated in figure 99 and described in the following steps. Note that the following description specifically involves the development of backward erosion piping in a situation where the conduit is surrounded by soils susceptible to this failure mechanism. A similar set of steps could be described for a scenario involving internal erosion rather than backward erosion piping, when the surrounding soils are not susceptible to backward erosion piping. For the sake of brevity, this description of similar steps in an internal erosion scenario is not repeated.

1. As water is impounded in the reservoir, seepage develops through the embankment dam. The time for this to occur varies with the permeability of the embankment zones. A phreatic line develops, and seepage forces are active in the saturated soils around the conduit.

2. Seepage can enter any defects in the conduit, if the conduit has an interior pressure lower than the water in the soil pores. If the seepage discharging into the nonpressurized conduit has sufficient gradient and soils are susceptible to backward erosion piping, soil particles may be carried with the water.

3. Backward erosion piping of the soils in the embankment dam will cause a tunnel to develop for soils that can support a tunnel. If the soils cannot support a tunnel, a sinkhole may occur instead. A failure can occur if the defect in the conduit is large enough to allow most of the reservoir water to escape.

4. If soils between the reservoir and the defect in the conduit are not susceptible to backward erosion piping, and no preferential flow paths occur in the surrounding soils, the defect in the conduit may not result in immediate problems.

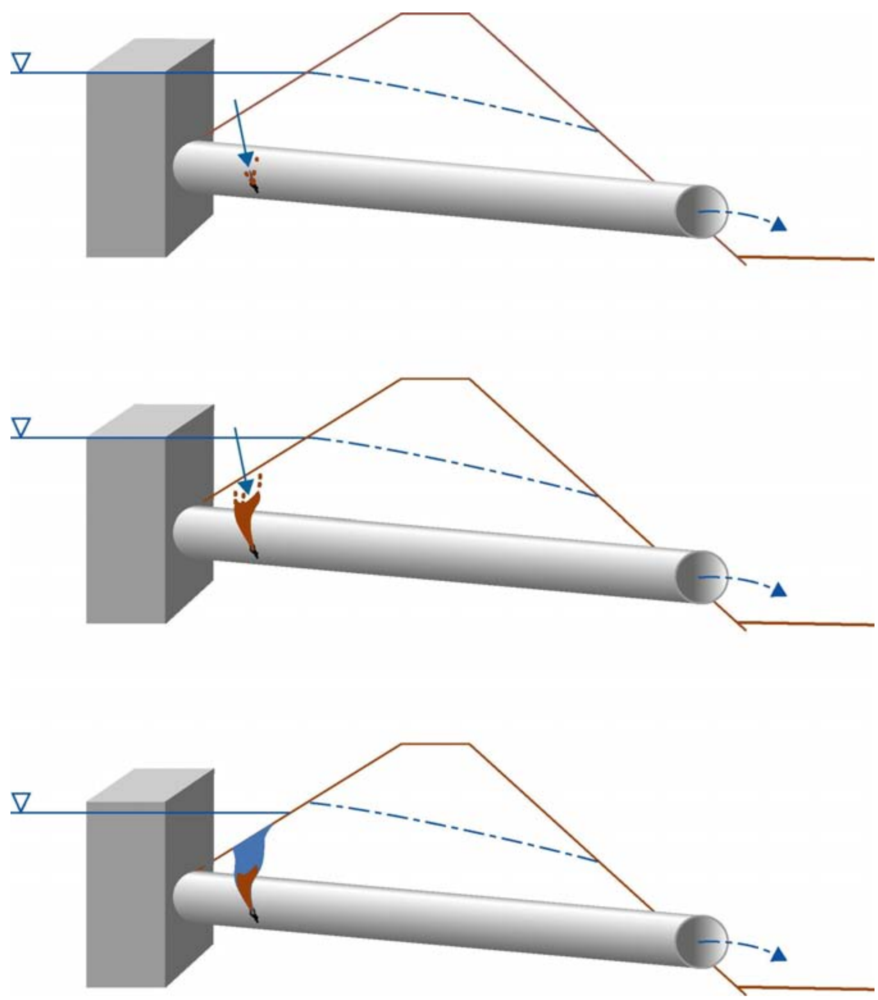


Figure 99.—Failure Mode No. 1.—Backward erosion piping or internal erosion of soils surrounding a defect in a nonpressurized conduit.

5. If a preferential flow path develops in the soils surrounding the defect in the conduit, such as a hydraulic fracture in the surrounding soils, then internal erosion will occur as water from the reservoir flows along the crack or other preferential flow path to the defect in the conduit.

6. The extent of the erosion that will occur depends on the velocity of the flow, the erosion resistance of the surrounding soil, the size of the preferential flow path, and the size of the defect in the conduit. The erosion that develops from internal erosion from a preferential flow path may have a similar appearance to that from backward erosion piping.

7. If the tunnel continues to develop from internal erosion and proceeds backwards until it reaches the reservoir, and the defect in the conduit is large enough, a breaching type of failure can occur. If the tunnel erosion does not progress completely until it reaches the reservoir, a complete breaching failure may not occur, but sinkholes may develop that must be repaired.

The *Introduction* of this document includes extensive discussions of factors that should be evaluated to determine whether internal erosion or backward erosion piping is the correct term to describe the mechanism of failure.

This type of failure mode was in progress at Tin Cup Dam (Luehring, Bezanson, and Grant, 1999). Numerous sinkholes developed in an embankment dam, when a masonry tunnel developed defects and the soils adjacent to the conduit were eroded into the conduit. Later, after the conduit was repaired, additional problems developed, as described under Failure Mode No. 2.

This type of failure mode can also occur where conduits have misaligned joints or irregularities in their walls. Joint offsets can cause high negative pressures to develop at overhangs during high velocity flow within the conduit. These offsets can create negative pressures at the offset from a Venturi effect. The negative pressures can pull or "suck" surrounding soils into the conduit through the opening, and voids can develop next to the conduit. Continued loss of surrounding soil could lead to development of a sinkhole, which, if it were to connect with the reservoir, could lead to serious consequences and eventually a disastrous failure of the embankment dam. Theoretically, this failure mechanism would develop as follows:

1. High velocity flow in a conduit with an joint offset or other irregularity in the walls causes a negative pressure to develop downstream of the offset or defect.

2. If a defect in the conduit wall or a joint that has separated occurs near the point of high negative pressure, the soil surrounding the conduit could be pulled into the conduit from the negative pressures, even though the conduit is flowing under pressure.

3. Continued removal of soil near the defect could result in a sinkhole, if it were allowed to continue and could even progress to connect to the reservoir or embankment surface.

This failure mechanism is less likely than the one where water under positive pressure is forced through the defect in the conduit and damages the surrounding soil (Failure Mode No. 2).

7.1.1 Design measures to prevent failure

Preventing this type of failure requires conduits to be properly designed and constructed with durable materials that are unlikely to develop defects. Chapter 2 discusses important design considerations for conduit materials. CMP's are particularly susceptible to this type of failure. Joints in articulated conduits must be designed to accommodate movement to tolerable limits to avoid separation of the joints.

Once soil around the conduit begins to move into a defect in a conduit, either from backward erosion piping or internal erosion, a serious problem exists. Quick action is usually advisable. Sinkholes can develop, and if the defect is large enough, perhaps an embankment dam breach could even develop. The only reliable long term solutions to preventing a failure or accident associated with this failure mode are to repair the defect in the conduit or renovate or replace the damaged section(s) of conduit. Short term remedial measures like grouting seldom are adequate to completely stop the seepage from moving the soil particles. Several options for addressing the defect in the conduit are available, including:

- Sliplining the conduit
- Removal and replacement of the conduit
- Repair of the conduit

Chapters 12, 13, and 14 have more extensive discussion on methods for renovation, removal and replacement, and repair of conduits.

Once a defect develops in a conduit, quick action is needed to prevent serious erosion of the surrounding soils. At Tin Cup Dam, an emergency repair involving sliplining a deteriorated 2- by 3-foot outlet works conduit (masonry pipe) with a 16-inch diameter HDPE pipe was implemented to address sinkholes that had formed above it (Luehring, Bezanson, and Grant 1999, p. 3). The annulus space between the HDPE slipliner and the masonry pipe was grouted, but the grout was later found to have floated the HDPE conduit, and sufficient grout was not injected to fill the annulus space completely. Later inspections showed that cavities were present next to joints in the masonry pipe that were not filled during the grout operations. Additional seepage problems became apparent soon after the repair. Consequently, extensive additional repairs were required the next year. This example illustrates how emergency repairs may avert an immediate threat, but may not be a suitable long term solution. This also illustrates that problems perceived to be associated with a conduit may have additional causes. In the final repair of the embankment dam, evidence was found of construction problems, including use of materials containing roots and other debris. Other poor construction practices and material incompatibility between portions of the embankment and coarse rock fill zones also contributed to problems at the site.

7.2 Failure Mode No. 2: Backward erosion piping or internal erosion of soils by flow from a pressurized conduit

When the conduit is flowing under pressure, the pressure in the conduit can exceed the pressure outside the conduit. If there are defects in the conduit, the high pressure flow can exit the conduit through the defects. The water flowing under pressure begins to exert hydraulic forces on the embankment soils. This could also occur, if a portion of the conduit has collapsed or articulated conduits separate at a joint. Water flowing in the conduit could then flow outward into the surrounding embankment through the defect in the conduit.

Conduits may collapse from deterioration, poor design and construction, and other causes, as discussed in chapter 8. If the conduit were to become blocked by debris, the internal pressure in the conduit could be much higher than the normal pressure at design flow. A conduit designed to flow without pressure may then become pressurized. Designers should consider this possibility. Separation of articulated conduits is discussed in section 4.3.1. The sequence of failure is described as follows and is illustrated in figure 100.

1. Water flowing out of the pressurized conduit begins seeping through the embankment dam and emerges at some exit face. The exit face may be the downstream toe, a downstream shell zone composed of very coarse gradation, or another seepage exit face. If the seepage face is unprotected by a properly designed filter, particles can be dislodged by the seepage water.

2. Seepage forces detach soil particles from the exit face, and backward erosion piping occurs if the soils are susceptible to this mechanism of failure and able to support a tunnel roof.

3. Backward erosion piping progresses backwards until a tunnel connecting the defect in the conduit and the exit face forms. If this backward erosion piping continues, it can lead to a failure of the embankment dam.

4. If the soils surrounding the conduit are resistant to backward erosion piping, the defect in the conduit is small, and the hydraulic force of water in the conduit is low, no immediate problems may occur. Soils not susceptible to backward erosion piping require a concentrated flow path for significant erosion to occur.

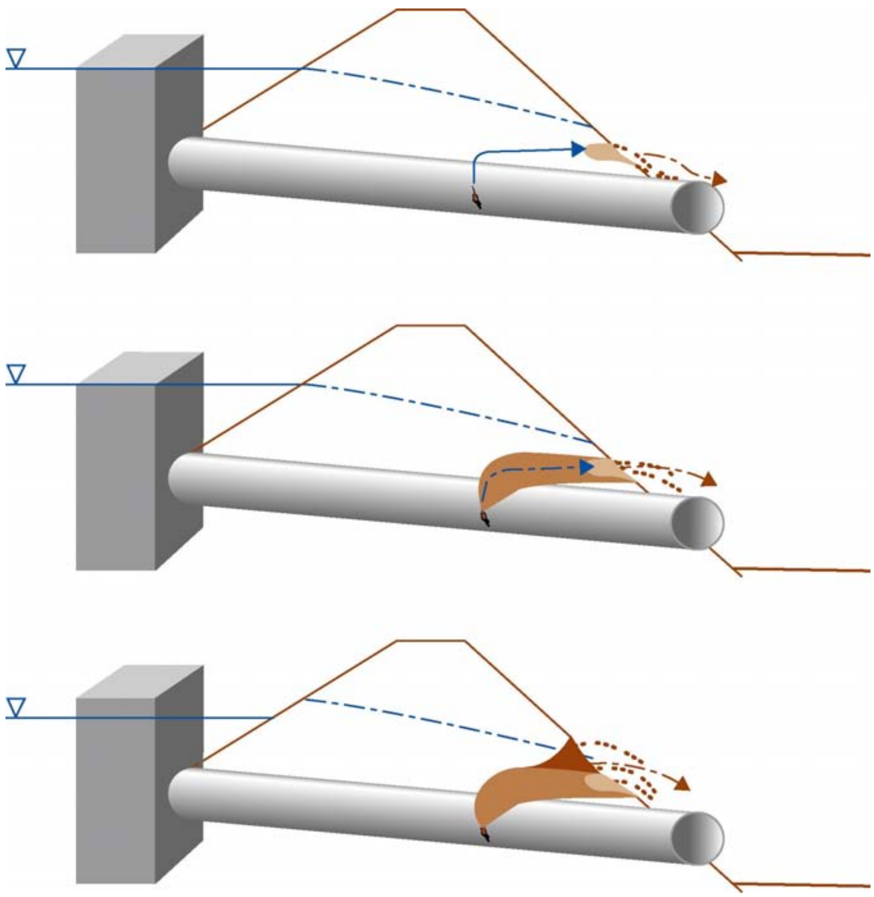


Figure 100.—**Failure Mode No. 2**.—Backward erosion piping or internal erosion of soils surrounding a pressurized conduit with a defect.

5. If soils surrounding the conduit develop a preferential flow path, such as a hydraulic fracture, and the internal conduit pressure is large enough, internal erosion may occur, rather than backward erosion piping. The hydraulic fracture created can erode and lead to development of a failure tunnel that is similar to that which develops in soils that are susceptible to backward erosion piping. If the erosion process continues, it can lead to a breaching failure of the embankment dam.

As previously discussed, Failure Mode No. 2 may involve either a backward erosion piping or internal erosion mechanism of particle erosion. The *Introduction* of this document includes extensive discussions of factors that should be evaluated to determine which of these mechanisms is likely for a specific situation.

An example of this failure mode is the breach of Lawn Lake Dam near Estes Park, Colorado, discussed in more detail in appendix B. A defective seam in the connection between a conduit and valve allowed water under pressure to erode the downstream soils by combination of internal erosion and backward erosion piping, and an embankment dam failure occurred. The failure occurred when lead caulking between the outlet conduit and gate valve deteriorated and allowed water under pressure to erode the embankment dam. The failure of Lake Tansi Dam (Heckel and Sowers, 1995) was also attributed to this type of failure mode.

In some cases, multiple failure modes may be involved at a single site. Tin Cup Dam developed sinkholes associated with Failure Mode No. 1, as described in the previous section, when the masonry outlet conduit collapsed. To address these problems, an HDPE pipe was sliplined in the masonry outlet tunnel and the annulus grouted. Additional sinkholes and distress symptoms related to Failure Mode No. 2 occurred when the downstream control gate that was installed as part of the first repair allowed pressurized flow in the conduit. More extensive repairs were required to address these second series of distress symptoms, including relocating the control gate back to the upstream side of the embankment dam and placing a downstream buttress fill (Luehring, Bezanson, and Grant, 1999, p. 7). Failure Mode No. 3, which is discussed in a following section, was probably also active at this site (see Failure Mode No. 3 for further discussion of Tin Cup Dam).

7.2.1 Design measures to prevent failure

Design measures that eliminate or reduce the possibility of a conduit deteriorating and developing a defect that would allow this failure mode include (1) using conduit materials that are resistant to deterioration, (2) ensuring watertight joints for pressure flow conduits, and (3) designing conduits to resist cracking from applied loads and foundation movements. Chapters 1 through 6 discuss many of these design measures in more detail.

Two general methods might be used to address this type of failure mode once it occurs. They are (1) barrier cutoffs, and (2) filter diaphragms and collars. A barrier cutoff consists of a grouted zone surrounding the conduit or sliplining of the conduit. The grout can be chemical or cementitious grout, depending on the size and shape of the suspected voids in the soil and the nature of the soils. For guidance on grouting around conduits, see section 14.1. Rarely would grouting be considered adequate without also installing an inverted filter over the area where seepage is occurring. An inverted filter is a series of layered filters placed on a soil surface that is discharging seepage. This filter is designed to filter any soil particles being discharged with the seepage and to provide capacity for releasing the collected water. The layers usually consist of a layer of finer sand placed on the ground surface where the seepage is discharging, which is covered by a layer of coarser gravel that is filter compatible with the fine sand. A third layer of small cobbles may overlay the gravel filter. In some cases, a fourth layer of rip rap size rock may be used to armor the filters beneath and protect them from damage. When multiple layers of filters are used to backfill a sinkhole, this system of filters may be placed in reverse order, with the coarser gradations placed in the bottom of the sinkhole, and progressively finer filters used to backfill the sinkhole. The intent of this system is to block additional movement of soils above the sinkhole into the feature. Ultimately, no remedial measure would be considered safe without repairing the conduit, because the hydraulic heads at the discharge point would be excessive for granular filter/drainage zones to control.

Filter diaphragms or collars that are limited in size are seldom sufficient to control this type of failure. Emergency action consisting of placing an inverted filter with rock cover over the discharge point of water or the face of the embankment dam may be appropriate. Rarely should this type of measure be considered a long term solution. If internal erosion rather than backward erosion piping is the cause of the problem, a filter blanket over the discharge area may become plugged, and flow will seek an alternative exit.

7.3 Failure Mode No. 3: Backward erosion piping or internal erosion of soils along the outside of a conduit caused by hydraulic forces from the reservoir

For this failure mode, water flows along the interface between the conduit through an embankment dam and the surrounding soil. This failure mode is usually associated with embankment seepage through the soils surrounding the conduit. The seepage along the interface between the conduit and surrounding soil may be concentrated enough to result in backward erosion piping, if the soils are susceptible. This failure mode is very similar to Failure Mode No. 2. The only difference in these two modes of failure is the source of the water. In Failure Mode No. 2, the source of the water causing internal erosion of the soils is a defect in a conduit. In Failure Mode No. 3, the source of the water is seepage from the reservoir that concentrates at the interface between the conduits and surrounding soil. The sequence of failure is described as follows and is illustrated in figure 101.

1. Seepage forces and concentrated flow develop along the contact between a conduit and surrounding soil.

2. Backward erosion piping can occur if the seepage exits downstream through an unfiltered face or into an overly coarse zone of the embankment dam and the soils surrounding the conduit are susceptible to backward erosion piping. Continued flow can result in the formation of a tunnel connected to the reservoir that will potentially result in a breach of the embankment dam.

3. If soils surrounding the conduit are resistant to backward erosion piping, but cracks or preferential flow paths occur from poor compaction techniques or later develop from hydraulic fracture, continued flow through the preferential

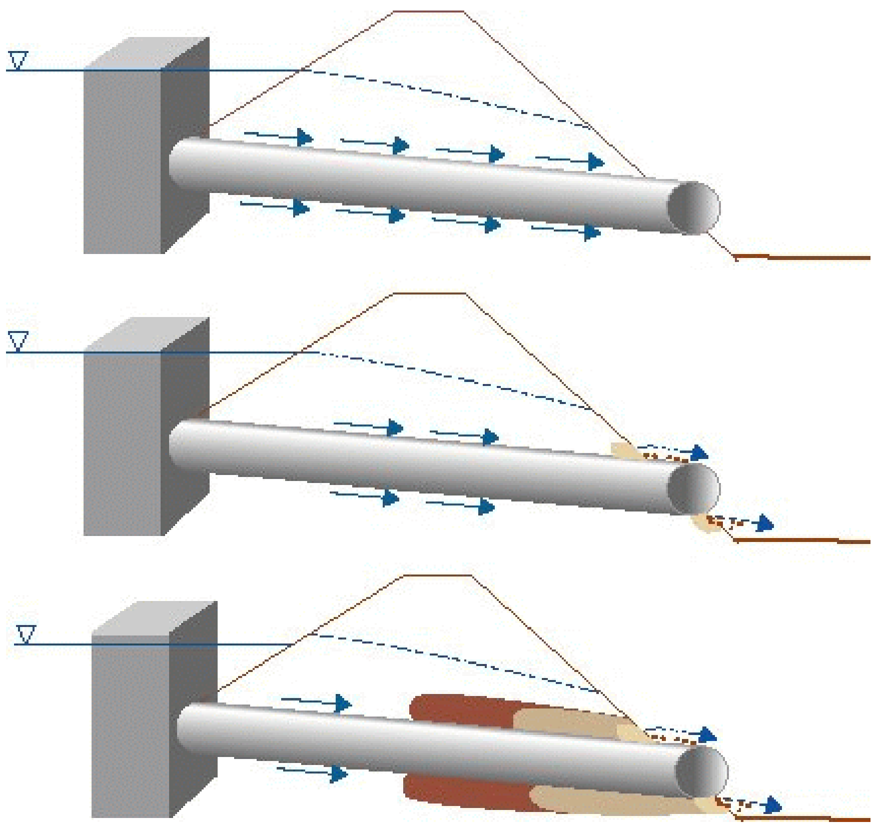


Figure 101.—**Failure Mode No. 3**.—Backward erosion piping or internal erosion of soils along a conduit at the interface between the conduit and surrounding soils.

flow paths will result in internal erosion. An erosion feature similar to that caused by backward erosion piping can then develop.

4. If the erosion process continues, it can lead to a breaching failure of the embankment dam.

As previously discussed, Failure Mode No. 3 may involve either a backward erosion piping or internal erosion mechanism of particle erosion. The *Introduction* of this document includes extensive discussions of factors that should be evaluated to determine which of these mechanisms is likely for a specific situation. Figures 8 and 9 illustrate failure mechanisms resulting from internal erosion along a conduit.

The Tin Cup Dam case history described by Luehring, Bezanson, and Grant (1999) is an example where this failure mode probably contributed to the development of extensive sinkholes and other distress symptoms at an embankment dam. As discussed previously in this chapter, it seems likely that multiple failure modes occurred at Tin Cup Dam, and water flowing along the outside of the conduit from the reservoir, Failure Mode No. 3, was one of them.

Compacting soil adjacent to a conduit is difficult, and compaction efforts can dislodge the conduit and create pathways for future concentrated flow. A cradle is needed, so that soil does not have to be compacted under the haunches of the conduit. This is important to prevent an easy pathway for internal erosion. For guidance on the design and construction of conduits and filters, see chapters 1 through 6.

Often, failures of embankment dams related to water flowing through or under the embankment have been near the conduit location. A natural tendency has been to assume that the pathway for water flow that caused the failure was directly along the conduit, identified as Failure Mode No. 3. This mode of failure appears most likely when soil is not compacted properly under the haunches of circular conduit, and a continuous zone of poorly compacted soil is subject to the hydraulic head of the reservoir. Examples of this type of failure mode are the Loveton Farms and Medford Quarry Dams Wash Water Lake case histories in appendix B.

One of the reasons that antiseep collars were used in embankment dam design was to prevent this mechanism of failure. The fact that many failures occurred even though antiseep collars were installed correctly, and that the collars could be seen to be intact after the failure caused investigators to consider that at least a portion of the flow path may have been away from the interface between the conduit and surrounding soil in some dam failures. Appendix A discusses in detail why antiseep collars have been discontinued as a primary defensive design element on most new embankment dams.

Figure 102 shows a conduit with its antiseep collars intact after an internal erosion failure of the embankment dam. In this case, it appears unlikely that the flow path for the failure was a continuous uninterrupted flow along the conduit, but at least part of the flow path was in the earthfill surrounding the conduit. In most cases, it has not been possible to determine the exact flow path that water followed in internal erosion failures, because the evidence was destroyed by the failure.
If hydraulic fracture and other causes of cracks in compacted backfill were ignored as the potential cause for failures, one might incorrectly assume that all failures that occur in the vicinity of conduits are attributable to flow along the conduit. In Failure Mode No. 4 (discussed in the following section), hydraulic fractures occur in the soil mass beyond the immediate vicinity of the conduit, usually associated with differential settlement in the fill caused either by the conduit or excavations made to install the conduit, or uneven bedrock profiles near the conduit.

Failures of compacted dispersive clay embankment dams, such as those experienced by the NRCS and documented in Sherard (1972), probably involve Failure Mode

Figure 102.—Conduit with intact antiseepage collars. The collars would have interrupted flow along conduit. Internal erosion or backward piping erosion likely occurred through hydraulic fractures in surrounding earthfill, resulting in failure of this embankment dam.

No. 4 more often than Failure Mode No. 3, where water is assumed to flow directly along the conduit. The reason for this conclusion is the known high quality of the compaction effort used to place low permeability clays around the conduits of these structures, plus several eyewitness accounts where the flow path was known to be as much as 15 feet above and to the sides of the conduit. The known cause of those failures was hydraulic fracture of the embankment dam, not always immediately in the vicinity of the conduit.

7.3.1 Design measures to prevent failure

A filter diaphragm or collar surrounding the conduit is the currently accepted method used to prevent this type of failure mode. Filter diaphragms and collars are discussed in detail in chapter 6. In summary, Failure Mode No. 3 refers to the condition where the predicted flow path for backward erosion piping or internal erosion is directly along the interface between the conduit and surrounding earthfill. Failure Mode No. 4, discussed in the following section, covers situations where the pathway for the erosion of the earthfill is a significant distance away from the interface of the conduit and embankment. Filter diaphragms or collars may need to be significantly larger to protect against Failure Mode No. 4 than are needed to protect against Failure Mode No. 3.

7.4 Failure Mode No. 4: Internal erosion of hydraulic fracture cracks in the earthfill above, below, or adjacent to the conduit

Conduits are one of the primary causes of differential settlement of an embankment dam that can result in hydraulic fracture of the embankment in the vicinity of the conduit. When an earthfill experiences hydraulic fracture, a pathway is created along which water from the reservoir can flow easily and erode the soil in contact with the crack.

Failure Mode No. 4 is one where hydraulic fracture of the embankment dam in the vicinity of a conduit is attributable to the differential settlement caused by the conduit, and flow through the crack erodes the embankment to the point where a breaching type failure occurs. Hydraulic fracture of earthfill is discussed extensively in section 5.2. This failure mode differs from Failure Mode No. 3, since the seepage path forms at a location away from the soil-conduit interface.

These kinds of failures are most common when a reservoir fills suddenly shortly after completion of the embankment dam, and the earthfill is highly erodible. The sides of cracks may erode very quickly when water from the reservoir flows through the crack. The eroded failure path can enlarge to a size that can empty a reservoir rapidly.

If a crack is not intercepted with a filter zone, an embankment dam failure can result when the crack enlarges from erosion. Even high plasticity clays that are not dispersive can erode over time. The sequence of failure for Failure Mode No. 4 is described as follows and is illustrated in figure 103.

1. After a crack forms in the soils surrounding the conduit, if the embankment soils are highly erodible, the crack rapidly enlarges from erosion of the sidewalls of the crack. The water discharging at the downstream face of the embankment dam is muddy, and a vortex may form at the entry point on the upstream slope.

2. The erosion tunnel enlarges to the point that the reservoir is emptied and the breaching process is completed.

3. A tunnel-shaped hole will exist after the failure, if the eroded tunnel is narrow enough to support the roof of the tunnel. If the tunnel collapses from erosion and widening caused by a lack of support for the roof, the failure will have the appearance of an open breach in the embankment dam.

4. As previously discussed, Failure Mode No. 4 almost always involves the mechanism of internal erosion, and very rarely can backward erosion piping be correctly attributed as the cause of such failure.

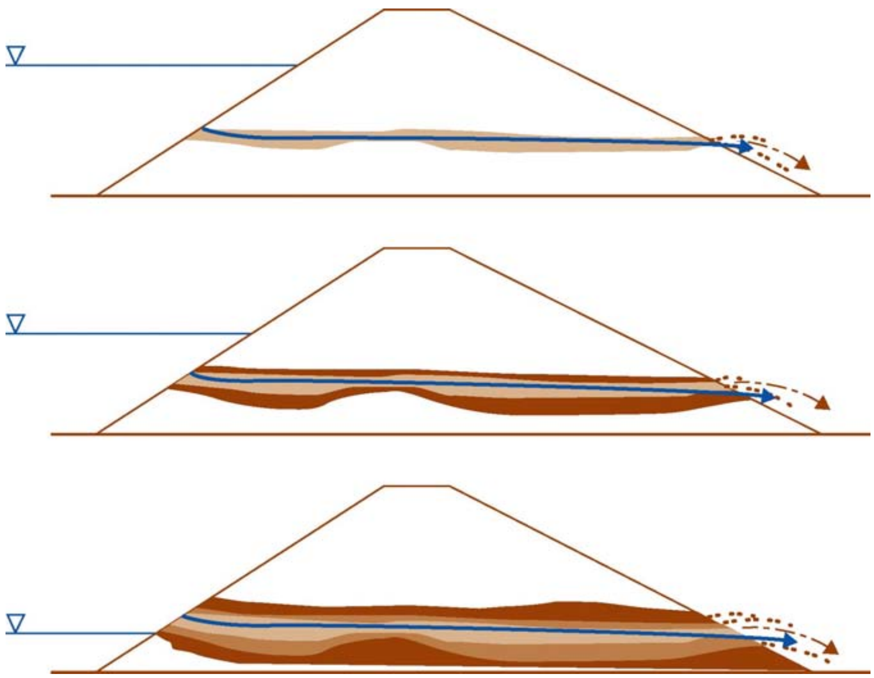


Figure 103.—**Failure Mode No. 4**.—Internal erosion of the earthfill above and on either side of a conduit caused by concentrated flow in a hydraulic fracture or other preferential flow path in the compacted earthfill. Hydraulic fracture cracks in the embankment dam may result from differential settlement caused by the presence of a conduit within the earthfill.

5. This type of failure occurs most frequently on first filling of the reservoir so that intergranular seepage rarely has had time to develop. One of the requirements for backward erosion piping to be defined in the context of this document is that it results from intergranular seepage, which justifies this conclusion.

6. Another reason that backward erosion piping is seldom the cause for failures in the earthfill above a conduit is that most embankment dams are not constructed of soils susceptible to backward erosion piping without proper design features to prevent the backward erosion piping.

As previously discussed, Failure Mode No. 4 almost always involves the mechanism of internal erosion, and very rarely can backward erosion piping be correctly attributed as the cause of such failure. This type of failure occurs most frequently on first filling of the reservoir, so that intergranular seepage rarely has had time to develop. One of the requirements for backward erosion piping to be defined in the context of this document is that it results from intergranular seepage, which justifies this conclusion. Another reason that backward erosion piping is seldom the cause for failures in the earthfill above a conduit is that most embankment dams are not constructed of soils susceptible to backward erosion piping without proper design features to prevent the backward erosion piping. The *Introduction* of this document contains extensive discussions of factors that are important in distinguishing between internal erosion and backward erosion piping mechanisms of particle erosion. Figure 7 illustrates the sequence in development of Failure Mode 4.

Figure 104 shows a small embankment dam that failed by internal erosion. The conduit created differential settlement in soils above the conduit that resulted in hydraulic fracture. The embankment soils were highly dispersive clays.

If the erosion tunnel widens enough, the tunnel can collapse, and a tunnel-shaped failure surface is not observed after the failure. The failure is simply a breach in the embankment dam.

The near failure of the USACE's Wister Dam is a good example of this scenario of internal erosion. The failure of the embankment dam during first filling was narrowly averted by quickly lowering the pool and employing other intervention measures. The embankment dam was constructed of highly dispersive clays without a chimney filter. The problems occurred in a closure section of the embankment dam. See the Wister Dam case history in appendix B. Sherard (1986, p. 911) provides further details on this interesting case history.

Another example of internal erosion resulting from the existence of hydraulic fracture cracks within an embankment dam is the Upper Red Rock Site 20 Dam. See appendix B for a detailed discussion of this case history.

Before the NRCS gained an understanding of the behavior of dispersive clay soils, over 15 embankment dams constructed of dispersive clays failed. Most of the failures occurred near the conduits through the embankment dam. The conduits contributed to differential settlement, which led to hydraulic fracturing (Sherard, 1972; Sherard, Decker, and Ryker, 1972a). Another example of this type of failure is the Anita Dam case history in appendix B. Investigators attributed one possible cause for the formation of a flow path for water to be freezing and thawing of soils adjacent to the conduit. Hydraulic fracture could also have contributed to the failure.

7.4.1 Design measures to prevent failure

Several design measures are available in preventing this type of failure mode from developing.

The first design measure involves reducing the potential for cracking and internal erosion of the fill. The mechanism responsible for this type of failure mode is

Figure 104.—Failure of an embankment dam due to internal erosion of hydraulic fracture cracks upon first filling of the reservoir.

hydraulic fracture. Hydraulic fracture is discussed in section 5.2. Dispersive clays are the most susceptible to this failure mode, and special attention should be given to testing for the presence of dispersive clays in all embankment dams. See section 5.3.3 for additional discussion of dispersive clays.

The second measure involves constructing a properly designed zone of filter material around the conduit to intercept cracks that develop from hydraulic fracture. Filter diaphragms, filter collars, or embankment chimney filter zones are common design elements. Most high and significant hazard dams will have as part of their design a full chimney filter. Low hazard embankment dams constructed of nondispersive soils may only include a filter diaphragm or filter collar. Filter zones are discussed in more detail in chapter 6.

A third measure to address the potential for internal erosion failures in embankment dams is the use of additives incorporated into the fill to reduce erosivity. Lime treatment has been used to reduce the erosivity of dispersive clays, but its cost is seldom justified, except in critical parts of the fill, such as the contact between the central core and bedrock. The case history on the Piketberg Dam in South Africa is discussed in appendix B, and it showed that the addition of gypsum to treat the dispersive clays in the core of the embankment dam may not have been completely effective. For guidance on soil amendments, see section 5.3.3. Usually, relying on a filter zone is considered more positive than using soil amendments.

Chapter 8

Potential Defects Associated with Conduits

Defects associated with conduits can lead to the development of potential failure modes. If corrective action is not taken to repair the damage resulting from the defect, this can lead to a failure of the embankment dam. For a further discussion of potential failure modes associated with conduits, see chapter 7. For guidance on the renovation, removal and replacement, and repair of conduits, see chapters 12, 13, and 14.

Various materials have been used in the construction of conduits, such as concrete, plastic, and metal. Each conduit material reacts differently in embankment dam applications. A search of the USACE's Waterways and Experiment Station damage and repair data base indicated that the most common defect requiring repair in concrete conduits was leakage through cracks and joints (USACE, 1988, p. 96).

This chapter will discuss some of the most common types of defects associated with conduits. Periodic inspection of the conduit by man-entry or CCTV inspection is the only reliable method to detect the extent of damage. For guidance on inspection, see chapter 9.

8.1 Deterioration

Often, if deterioration is left unchecked, it will continue and progressively worsen. If repairs are promptly made, the conduit may be able to continue to function in a serviceable fashion. However, if deterioration is allowed to progress, there may come a time when a significant portion of the conduit must be entirely replaced. Action for timely repair may be more cost effective than postponing repairs and eventually having to replace major portions of the conduit.

8.1.1 Abrasion

Abrasion in conduits is an erosional process and is a function of velocity and turbulence in the flow, the hardness of the abrasive material, and the quality of the surface experiencing abrasion. Abrasion is caused by water flowing through a conduit at high velocities and containing silts, sands, gravels, or stones (figure 105).

Figure 105.—Abrasion/erosion damage to concrete from flowing water containing sand and silt.

This flow causes a scouring or grinding effect on the exposed surface. Most conduits do not carry significant amounts of abrasive materials in the flow. However, conduits used for diversion during construction or for reservoir sediment release are especially vulnerable. Increases in the velocity of the flow can increase the abrasive power.

In concrete conduits, abrasive damage has been experienced in concrete with low strength and poor quality aggregates. Abrasive flow usually erodes the cement mortar mix matrix, leaving an exposed, polished, and coarse aggregate surface. As the abrasion process continues, the concrete may be eroded down to the reinforcement. The extent of damage depends on the flow duration and velocity, concrete quality, and compressive strength. In concrete conduits, abrasion is generally not a factor when velocities are less than 15 ft/s. In metal conduits, abrasive flow can erode protective linings and coatings and expose the surface to corrosion.

Once damage from abrasion has begun, it will accelerate with each operation of the conduit, unless the source of the abrasive materials is removed. Cavitation may also be triggered by the abrasion damage (by creating a flow surface irregularity) and greatly increase the rate of destruction.

Polyethylene plastic pipe has been found to be very abrasion resistant. However, high velocity flow containing abrasive materials can still be problematic for any type of pipe.

8.1.2 Aging

The aging process can also cause deterioration in conduits. In concrete, properties change over time and eventually affect the integrity of the structure (Pinto, 1994, p. 1111). Both the quality of concrete (e.g., porosity), and physical and chemical factors influence the rate of concrete deterioration. Processes that can weaken concrete include:

- *Freezing and thawing.*—Repeated cycles of freezing and thawing can affect the durability of concrete. Concrete readily absorbs water and is vulnerable to damage, if the water within its system of pores can freeze and generate disruptive pressures. If the pores existing in the concrete are inadequate in size and number to accommodate the greater volume occupied by the ice, the concrete will fracture. The rate of progression of the freezing and thawing deterioration will depend upon the number of cycles, the degree of saturation during freezing, the porosity of the concrete, and the exposure conditions. Concrete experiencing damage by freezing and thawing is characterized by a disintegrated appearance. Deterioration due to freezing and thawing is especially severe in the northern and mountain zones of the United States. Deterioration from freezing and thawing progresses from the exterior surface to the concrete inward. As the concrete on the surface fails and is removed by spalling, the depth of freezing progresses inward (Reclamation, 2003, p. 7). Freezing and thawing typically is not a significant concern for conduits, since most of the conduit is submerged or has limited exposure. However, freezing and thawing can become a problem for entrance and terminal structures. Figure 106 shows a concrete intake structure that has been exposed to repeated cycles of freezing and thawing. In new construction, the entrainment of small bubbles of air into fresh concrete has been found to provide relief for pressures developed by free water as it freezes and expands. Repairs to existing structures require replacement concrete or epoxy-bonded concrete (Reclamation, 1997, p. 26).

Figure 106.—Concrete deterioration from freezing and thawing.

- *Alkali-aggregate reaction*.—Alkali-aggregate reaction (AAR) occurs when certain types of sand and aggregate (e.g., opal, chert, flint, or volcanic material with a high silica content) are exposed to sodium and potassium hydroxide alkalies in portland cement. In a moist environment, a gel is formed around the reactive aggregate, creating tension cracks around the aggregate and extensive expansion and fracturing of the concrete. This expansion, cracking, and loss of concrete strength can lead to pathways for seepage or localized collapse of the conduit. Concrete containing alkali-reactive aggregate may show immediate expansion and deterioration, or it may remain undisturbed for many years. Concrete experiencing AAR is characterized by pattern cracking on the surface. Figure 107 shows a concrete wall that has experienced AAR. In new construction, aggregate sources containing negligible potentially alkali-reactive materials, low alkali cements, and pozzolan replacement of a portion of cement, should be used. When abundant potentially alkali-reactive materials are available, low alkali portland cements and fly ash pozzolan have been found to eliminate or greatly reduce the deterioration of reactive aggregates. There is no proven method for eliminating AAR in existing structures (Reclamation, 1997, p. 6).

- *Sulfate attack*.—Sodium, magnesium, and calcium sulfates existing in soils and groundwaters react chemically with the hydrated lime and hydrated aluminate in the cement paste in concrete. The volume of the reaction byproducts is greater than the volume of the cement paste from which they are formed, resulting in disruption of the concrete from expansion. Concrete experiencing sulfate attack is characterized by a disintegrated appearance. In new construction, a sulfate resistant portland cement or a combination of suitable cement and pozzolan should be specified, when it is recognized that concrete will be exposed to soil and groundwater with sulfates. The application of a thin polymer concrete overlay or sealing compounds may be beneficial for existing structures experiencing sulfate attack. Otherwise, removal and replacement of concrete with a sulfate resistant cement should be considered (Reclamation, 1997, p. 23).

Polyethylene plastic pipe, if exposed to ultraviolet (UV) radiation and oxygen, can experience degradation affecting the physical and mechanical properties of the pipe. Ultraviolet light is present in sunlight. Typical applications using polyethylene pipe involve sliplining of existing conduits. In this type of application, exposure to UV light is limited. Any exposed surfaces would require long term UV protection. This protection is provided by compounding 2 to 3 percent carbon black into the material, which prevents UV penetration.

8.1.3 Cavitation

Cavitation is an erosional process and often causes deterioration in concrete, plastic, and metal conduits with high heads, where high velocity vortices are formed. The

Figure 107.—Concrete deterioration from alkali-aggregate reaction.

risk of cavitation can be evaluated by computing the cavitation index for flow, which is a function of velocity and pressure. Normally, for flow velocities less than 40 ft/s, cavitation will be minimal. Discontinuities or irregularities on flow surfaces and/or misalignments in conduits carrying high velocity flow can induce cavitation. These discontinuities, irregularities, or misalignments cause the flowing water to separate from the conduit surface, resulting in negative pressure zones and bubbles of water vapor. When these bubbles travel downstream and collapse next to the conduit surface, the high pressure impact removes small particles of the conduit surface (pitting). As the pitting continues, a progressively deepening cavity develops, which causes additional irregularities that leads to even larger cavities farther downstream (also known as a Christmas tree pattern). Cavitation is common just downstream of mechanical control equipment, such as gates or valves (figure 108) where pressure flow changes to free flow. Damage from cavitation and abrasion can appear to be similar. Cavitation damage appears as a plucking out of the surface material with no fine scale evidence of flow direction. Abrasion damage is normally flow directional.

The use of aeration devices (e.g., ramps and/or slots) installed along flow surfaces in modern structures has been found to be an effective method for preventing cavitation damage. All new structures should include aeration devices, and existing structures that have experienced cavitation damage can be retrofitted to include these. However, the most effective solution is to eliminate the source of the cavitation, rather than attempting to minimize the resulting damage. For further guidance on cavitation, see Reclamation's *Cavitation in Chutes and Spillways* (1990a).

Figure 108.—Cavitation damage to the cast-iron lining of a conduit immediately downstream of a slide gate, caused by high velocity flow.

8.1.4 Corrosion of metals

Corrosion of metals is a complex phenomenon involving many inherent structural and environmental factors. Corrosion is commonly a result of contact between dissimilar metals, or when metals are in contact with water, moist earthfill, or the atmosphere. Corrosion affects all types of metal and alloy pipe and reinforcing bars in concrete. Corrosion is the destructive attack on conduit materials by electrochemical reaction to the environment. Corrosion can also be described as the process whereby metals return to their natural state. Certain metals, such as platinum, gold, silver, and copper exist in nature in a stable metallic state. However, other metals require refinement by heating. Unless these refined metals are protected from the environment, they will eventually revert from their temporary refined metallic state back to a more natural state. The soil and water surrounding the conduit, and water flowing through the conduit can affect the rate of corrosion. The soil and water can contain different types of acids, alkalis, dissolved salts, organics, industrial wastes, mine drainage, etc. The rate of corrosion will vary, depending on chemical and physical properties and exposure to the environment. Factors that influence corrosion include (American Iron and Steel Institute, 1994):

- *Soil resistivity*.—Corrosion involves the flow of current from one location to another. The ability of soils surrounding conduits to conduct electrical particles can affect their tendency to corrode a conduit. Resistivity is a measure of the resistance to current flow of a material, usually expressed in units of ohm-cm. Conduits surrounded by clay soils with typical resistivity values of 750 to

2,000 ohm/cm will be more likely to corrode than conduits surrounded by sands that typically have resistance values of 30,000 to 50,000 ohm/cm.

- *Acidity (pH)*.—Most soils fall into a pH range of 6 to 8, which is neutral. Water and soils with lower pH values are acidic and can result in a more corrosive environment.

- *Moisture content*.—Soils that drain rapidly are less corrosive than soils that tend to hold water longer. Soils with high clay content are typically more corrosive than sandy soils.

- *Soluble salts*.—Salts that become ionized can decrease the resistivity of a soil.

- *Oxygen content*.—Increasing levels of dissolved oxygen can accelerate corrosion.

The process of corrosion can proceed either uniformly or in pitting of the surface. Uniform corrosion is where corrosion occurs evenly over the surface, resulting in a low rate of corrosion. Pitting corrosion is not uniform and is focused only on a small surface area, resulting in a high rate of corrosion, until a perforation eventually develops. Pitting can begin on surface imperfections, scratches, or surface deposits. Between pH 5 and 9, pitting is likely to occur, if no protective film is present.

In the past, CMP has been a commonly used material for conduits through embankment dams. Thousands of embankment dams in the United States and all over the world have CMP conduits installed in them. Corrosion is a common problem with CMP conduits (figure 109). Many State highway departments have made extensive studies on the use and durability of CMP for culverts under highway embankments. However, available information on the use of CMP for conduits through embankment dams is limited. A study of 50 existing CMP conduits in watershed dams located in the Midwestern United States was done in 1989 (Koelliker and Lin, 1990). The study determined that the estimated average life of the sampled CMP conduits was 43 years, but the lifespan ranged from 24 to 72 years. This study also found that leakage and associated corrosion at pipe joints was most often the primary limiting aspect of life expectancy. Many spillway conduit systems constructed with CMP experience corrosion at the joint connection between the conduit section and the riser (the vertical pipe or inlet that connects to the outlet pipe). Spillway risers are subject to deformation and movement (tilting) caused by ice loadings or erosion, which can open the joint connection with the outlet pipe. The riser itself is also susceptible to corrosion.

The most susceptible portion of a CMP to corrosion is the invert, since it is exposed to the flow of water for the longest length of time. CMPs that have inverts with sags could trap water and further increase the potential for corrosion. Corrosion of

Figure 109.—Corrosion has completely destroyed this CMP spillway conduit. Backfill materials that surrounded the conduit have been eroded by flow within the conduit.

CMPs generally consists of two types: soil side or water side. Most metal loss associated with corrosion occurs on the interior or water side of the pipe. Soil side corrosion is not usually a significant factor in conduit life. In the presence of oxygen and water, metal corrodes through an oxidative process that involves the formation and release of metallic ions. The water acts as an electrolyte to carry these ions, which form the basis for the corrosion of the CMP. The reaction of the metal with the dissolved oxygen in the water causes the deterioration most visible on the water side of the conduit (Federal Highway Administration [FHWA], 1991, p. 4). CMPs are subject to electrolytic corrosion due to galvanic action between the metal and the surrounding soil, groundwater, and water flowing through the conduit (Kula, Zamensky, and King, 2000, p. 2). The galvanic action results in corrosion of the CMP and a gradual decrease in wall thickness and structural integrity. Over time, corrosion of the CMP will result in the reduction of wall thickness, formation of pipe perforations, and the eventual collapse of the CMP.

The service life of the CMP is affected by its metallic makeup, coatings, linings, pH and resistivity of the backfill and water, moisture content of the backfill, and abrasion from material particles in the flow. Pipe manufacturers have applied coatings and linings to CMP to mitigate corrosion and extend the service life. CMP coatings have included metallic coatings (zinc [galvanized] and aluminum), and nonmetallic coatings (bituminous [asphalt], cement, and polymers). CMP linings have included asphalt and concrete. The natural scaling tendencies inherent in some waters provide additional protection. Scaling is the deposit and adherence of insoluble products on the surface of the CMP, which isolate it from the water and protect it from corrosion. The factor that most affects corrosion and scale formation in the CMP are the chemicals dissolved in or transported by the natural water. All coatings and linings have some minor flaws (holidays). Corrosion tends to concentrate at these flaws, since water can seep between the coating or lining and the base metal moisture can become trapped, increasing the rate of corrosion. Thus, it may be possible for a coated CMP to become deteriorated in less time than an uncoated CMP in the same environment. Coatings applied to existing surfaces of conduits are generally not very effective due to difficulties involved in obtaining a good bond with the conduit surface.

For guidance on estimating the service life of CMP conduits, see the National Corrugated Steel Pipe Association's *CSP Durability Guide* (2000) and FHWA's, *Durability of Special Coatings for Corrugated Steel Pipe* (1991). Caution should be exercised in attempting to determine the service life of CMP used in conduits through embankment dams. Many of these CMPs may have used no corrosion protection, and many of the coatings and linings available today were not available when the embankment dams were originally constructed. Prior to 1950, galvanized steel was the only metallic coating available for CMP. If a CMP has experienced denting during installation, this could result in corrosion in areas where the protective coating has been damaged. Figures 110 through 113 show the results of corrosion affecting CMP outlet works conduits.

Corrosion of reinforcement in concrete conduits can also occur when it becomes exposed. Reinforcement can become exposed by cracking or spalling of the concrete (figure 114), inadequate cover, or porous concrete. When reinforcement is exposed to corrosive elements, the iron oxides formed expand (requiring more space within the concrete than the original reinforcement), resulting in tensile stresses within the surrounding concrete. These tensile stresses cause cracking and delamination of the concrete. Rust stains on the conduit surface may be an indicator of reinforcement corrosion.

Cathodic protection attempts to retard electrochemical corrosion through the application of reverse direct current to the protected metal and to another metal which acts as a sacrificial anode. This sacrificial anode, typically consisting of either zinc, magnesium, graphite, or aluminum alloys, must be periodically replaced. New concrete installations in hostile corrosive environments should place special attention on crack widths and concrete cover, as well as consider the use of protective coatings, before considering this often problematic and costly means of protecting against steel corrosion. Galvanic reaction between dissimilar metals can also result in corrosion. This can occur when a galvanic reaction forms between reinforcing steel and stainless steel outlet works components.

Another form of corrosion is bacterial corrosion (Patenaude, 1984) caused by anaerobic sulfate-reducing bacteria. Bacterial corrosion typically has been found to occur on galvanized steel pipe. This type of corrosion can exist in two environments