PIPING, SEEPAGE, CONDUITS, and DAM FAILURES

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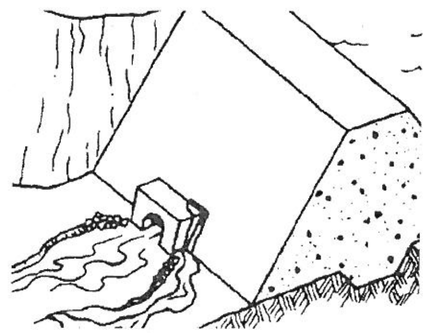
Abstract

Many failures of small to medium embankment dams are related to internal erosion of soil by seepage along conduits. For most of the 20th century, engineers attempted to prevent these failures by construction of "anti-seep collars" on the conduits to prevent seepage from occurring along the conduits. However, dam failures caused by seepage along the conduits or through the adjacent fill continued to occur.

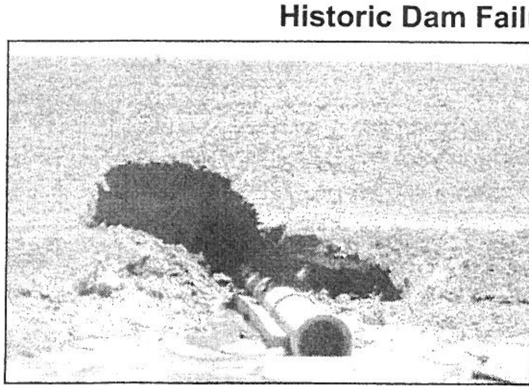
Publication of research by the Natural Resources Conservation Service (NRCS, formerly SCS), Bureau of Reclamation, Army Corps of Engineers, and others about 20 years ago resulted in recommendations for controlling seepage along conduits by the use of 'filter diaphragms", typically located in the downstream portion of the dam. Properly designed, these filters have been shown to be effective for intercepting and controlling seepage along the conduit (and also through cracks in the embankment around the conduit) and for preventing the migration of soil particles that could lead to internal erosion and dam failure.



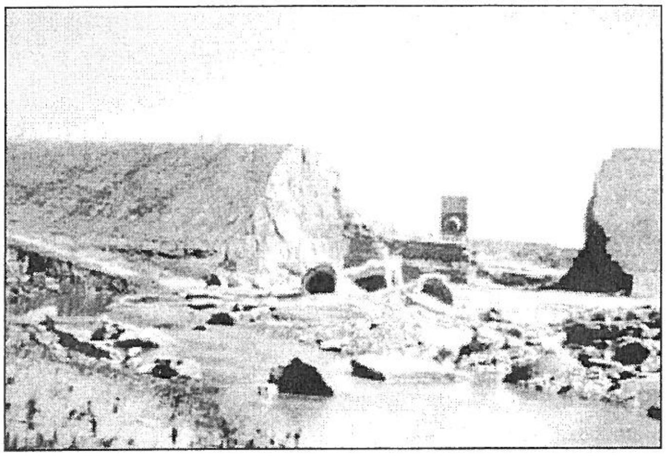
Seepage around conduit (from Colorado Dam Safety Manual)

However, many dam design references, guidelines, and regulatory agencies still allow, or worse, even require, anti-seep collars. Also, engineers who may have been designing impounding structures for a long time are reluctant to change from the traditional design methods employing anti-seep collars. This paper summarizes current design recommendations contained in a soon to be published guidance document called "*Conduits through Embankment Dams - Best Practices for Design, Construction, Problem Identification and Evaluation, Maintenance and Repair*" is being developed by engineers from USBR, Corps of Engineers, NRCS, FEMA, and ASDSO.

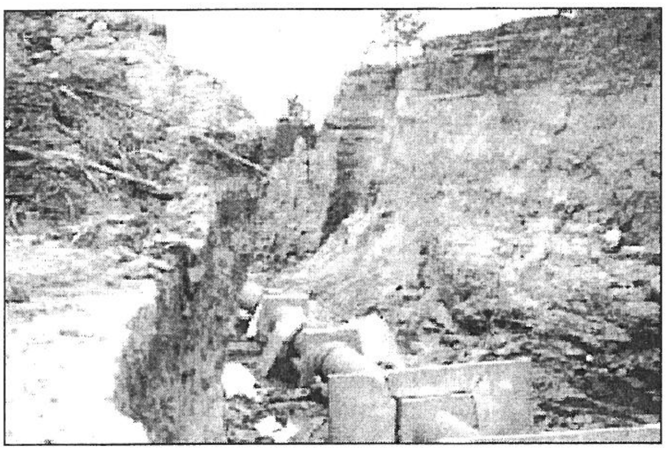
Historic Dam Failures and Anti-Seep Collars



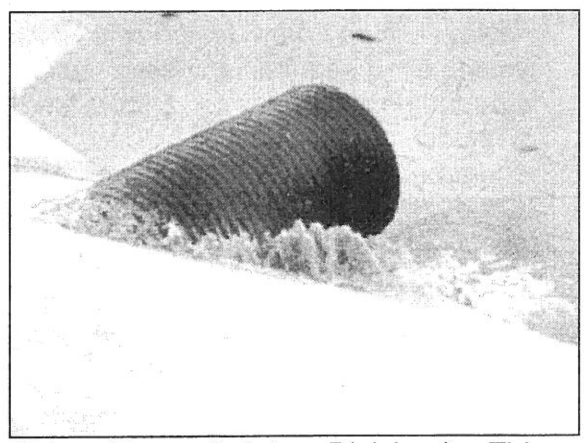
The failure of the "Owl Creek Site 7" dam shown at left occurred during first filling in 1957 (photo by provided by Danny McCook, NRCS). The failure was investigated by James Sherard and published in 1972 (Sherard, 1972). In another 1972 report, Sherard, Decker and Ryker (1972) note that although the seepage followed the conduit in the downstream portion of the dam, the seepage did not initiate near the conduit at the upstream end. Instead, it was determined that seepage initiated in a crack near the left abutment, where it followed the dam/foundation interface along the upstream side of the cutoff trench until it reached the conduit. Seepage was then apparently able to make its way to the downstream end of the dam, eroding away the surrounding embankment soils.



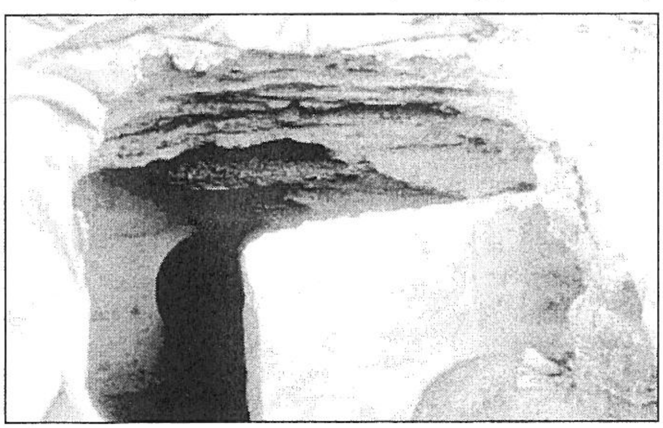
The embankment failure at left was caused by internal erosion of fill near the conduit. The initial failure was tunnel shaped, but the collapse of the roof of the tunnel resulted in the observed shape of breach. Hydraulic fracture in highly dispersive clay embankment soils caused the failure. The embankment design included anti-seep collars but no filter diaphragm (USBR, 2004).



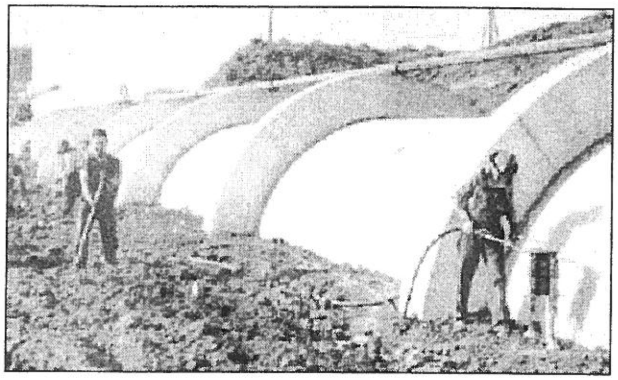
Failure of a dam following first filling due to internal erosion along the conduit. (USBR, 2004). Clearly, the anti-seep collars did not prevent a seepage failure.



At right, seepage is exiting the downstream slope of a dam along the outside of a spillway conduit. (Photo from USBR, 2004, provided by Ohio Dam Safety Division.) This seepage flow is carrying soil fines and failure of the dam is imminent.



Anti-seep collars are unable to prevent this type of flow and subsequent dam failure.

Part of the problem with anti-seep collars is that good compaction in the critical zone around the conduit is difficult to achieve. Also, the backfill is likely to have different density, strength, and compressibility than the rest of the dam embankment, leading to the possibility of differential settlement and cracking of the fill. (above photos from USBR, 2004).

Piping, internal erosion, and embankment cracking

Frequently, the term "piping" has been used to describe dam failures caused by loss of soil resulting from uncontrolled seepage along a conduit or through cracks in the dam embankment. However, this process is now termed "internal erosion" (McCook, 1998). An excellent discussion is a paper by Martin (1990). Sherard (1953) described the process:

> *"... the seepage takes place in the form of well defined water veins. The leak gradually enlarges the channel until failure occurs. The erosion starts at the exit and works back toward the reservoir. These channels follow paths of maximum permeability and may develop after many years of successful operation. They have been attributed to flow through inadequately compacted material, along outlet conduits, between the embankment and the foundation or abutments and through relatively pervious horizontal compacted layers.*
>
> *Pipes initiating after construction have been attributed principally to drying cracks, animal burrows, and leaks in outlet conduits. The water may first emerge as a small spring, which gradually becomes larger over a number of years. In other cases, a large flow of muddy water may precede complete failure by only a few hours."*

Cracking may occur in an embankment dam can occur for many reasons, including differential settlement and "hydraulic fracturing". Seepage through transverse cracks (in the upstream to downstream direction) obviously can lead to dam failure.

Differential settlement cracks can occur near a conduit because the backfill under and around the conduit may have different compressibility than the foundation soils under the remainder of the dam. Differential settlement cracks can also occur anywhere that the foundation is not uniform. McCook (1997) gives a "rule of thumb" that differential settlements of the magnitude of about 1.0 foot over a length of 100 feet can result in cracking of embankments. In cases where a soft foundation may result in relatively larger settlements, the engineer should estimate the potential for lateral spreading of the foundation as a result of "squeezing" of soft soils from the weight of the dam embankment. Embankment cracking should be anticipated when the ratio of horizontal to vertical movement exceeds a value of about 0.4 (Bushell, Butler, Walton, and Mathur, 2002).

McCook (2002) mentions that embankment cracking may be minimized by compacting the embankment soils at moisture contents on the wet side of the optimum moisture content (up to 3% above optimum) as determined by the "Standard Proctor" test. Wetter soils are more flexible than drier soils, so that they can more easily tolerate differential settlements without cracking. Therefore, it is better to specifying placement moisture content ranges of –1% to +3% wet of optimum instead of the typical –2% to +2% of optimum. Even then, for maximum flexibility, compaction below the optimum moisture content should be avoided if possible. For dams less than about 60-100 feet in height, excess pore pressures due to compaction of wet fill should not be a problem. (Also, note that use of the "Modified Proctor" test is not recommended as the control standard for construction of dam embankments, as the resulting optimum moisture content is drier than the Standard Proctor value, so the embankment will be more brittle and more likely to crack as a result of differential settlement.)

Nearly all embankment dams have the potential to crack by "hydraulic fracturing". Talbot (1988) provides a good description of hydraulic fracturing:

> *"Evidence indicates that hydraulic fracturing occurs in most earth dams, including small and medium sized dams. The process includes some differential settlement under or in the embankment soil that cause lateral stress relief. Water pressure exceeding the lateral soil pressure is directed into the soil mass on the wetting front as the embankment saturates during the first filling thus causing cracks or joints in the embankment. Cracks are usually narrow and in many cases are likely to swell shut making them difficult to detect. When the dam is constructed of dispersive clays or other highly erosive soils and without a protective filter zone within the embankment, concentrated leaks usually develop and progress to failure if not checked. Since hydraulic fracturing occurs in most dams, there is always a chance that soil swelling during the wetting process may not be rapid enough to prevent erosive velocities in the cracks. Sand and gravel filters are a positive*

line of defense against concentrated leaks and embankment failure caused by hydraulic fracturing."

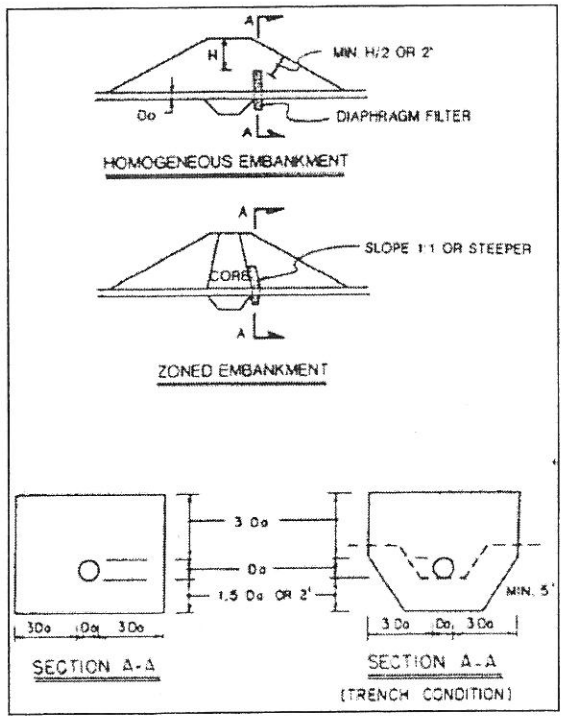
Filters and Filter Diaphragms

Criteria for designing embankment dam filters to prevent internal erosion are well established (NRCS 1994, USACE 1994, and USBR 1999). McCook (1997) summarized leading expert opinions:

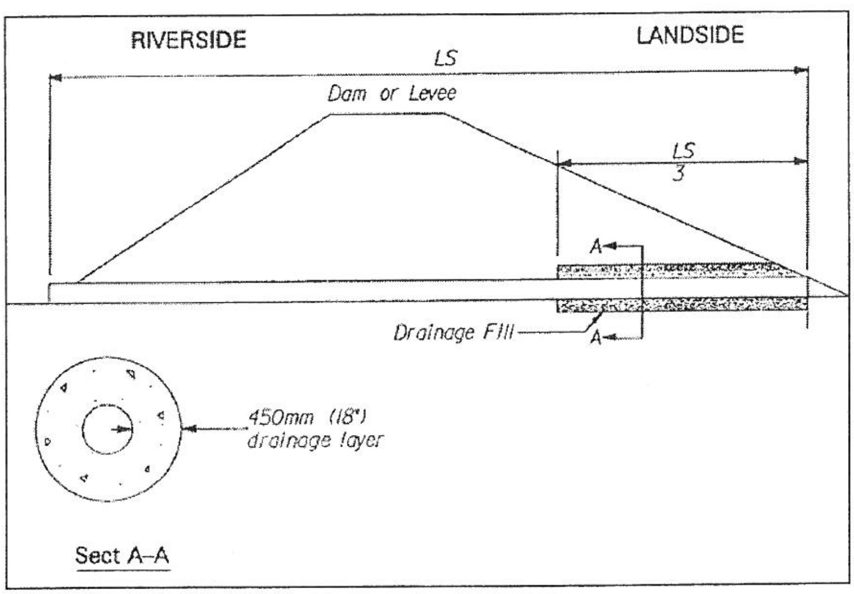
> *J. L. Sherard in numerous publications related his experience and opinion that a properly designed chimney filter/drain is an essential ingredient in many embankment designs. Several notable quotations are summarized as follows:*
>
> *Sherard (1973) stated "The writer believes that the time has come when it should be considered prudent to require at least a thin chimney of filter material in low homogeneous dams, except in circumstances where failure would not cause loss of life or important property damage."*
>
> *Sherard (1985) stated the opinion slightly differently, "Both experience with dam behavior and recent laboratory research show conclusively that concentrated leaks are reliably controlled and sealed by adequate filters, even under the most extreme conditions.*
>
> *Sherard (1985) followed, "It is now clear that the most important element in the dam is the filter (or transition zone) downstream of the core. By providing a conservative downstream filter, we can quit worrying about possible concentrated leaks through the core. ... Almost all records of damage or failure from leakage and piping have been for dams in two specific groups:*
>
> *(1) homogeneous dams without chimney drains (vertical filter-drains), in which a concentrated leak develops through the dam and exits on the downstream slope without passing through a filter; and*
>
> *(2) dams with impervious sections consisting of coarse, broadly graded soil for which excessively coarse filters were used."*
>
> *"Several important factors determine the need for an chimney filter/drain in the design of an embankment. Some situations may require only a partial chimney filter/drain, along a portion of*

the embankment length, or adjacent to appurtenances such as conduits extending through the embankment."

Less well established are the dimensions and required locations of filter zones in a dam. NRCS publications TR-60 (1990) and SNTC Technical Note 709 (1989) provide some design concepts for new construction. The figure at right (from Hall, 1987) summarizes those recommendations.



The Corps of Engineers' guidance manual for pipes through dams and levees (USACE, EM 1110-2-2902, 1998) suggests surrounding the downstream third of the pipe with a filter (drainage fill):



McCook (1997) provides some general guidance on the size and location of chimney drains and filter diaphragms around conduits:

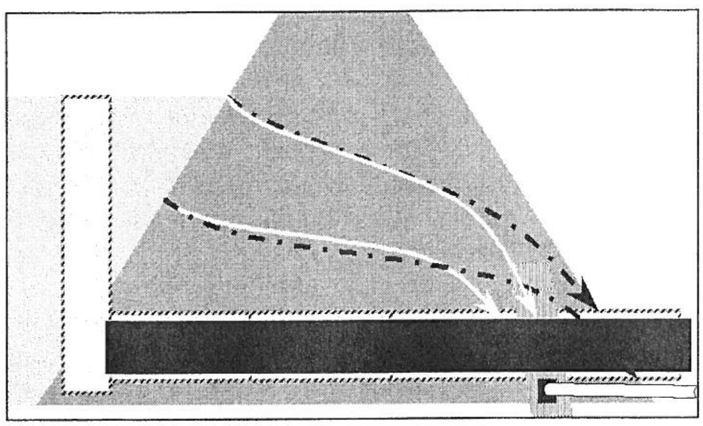
> *<u>Dimensions</u>. The width of an embankment chimney filter/drain zone depends partially on the equipment used for construction. In a typical method of construction, a backhoe is used to excavate a trench which is backfilled with drain fill. In this method of constructing a vertical chimney filter/drain, a typical width is 3 feet. Chimney filters built on a slope within the embankment require a width at least equal to the width of the spreading or placement equipment. Special spreaders may be fabricated to allow use of a zone narrower than typical front end loaders or other typical placement equipment. Forming of the drain zone will add to the expense of construction.*
>
> *<u>Lateral and Vertical Extent</u>. If embankment soils have a low resistance to cracking, and differential settlement cracking is expected along most of the embankment alignment, the chimney filter/drain zone should be carried from abutment to abutment, and it should extend from the flood plain surface upwards to the elevation of the permanent water level in the upstream reservoir, as a minimum. Because many failures addresses by a chimney filter occur during first filling, some designers don't consider it necessary to extend the chimney zone to a higher elevation. A designer who wishes more confidence would extend the zone to the highest elevation to which water could potentially be stored, even temporarily, in the reservoir.*
>
> *<u>Filter Diaphragms around Conduits</u>. If the only anticipated cracking or hydraulic fracture potential problems are associated with the conduit extending through the embankment, then a filter diaphragm surrounding the conduit may be the only chimney filter/drain feature required in the embankment design. NRCS policy requires a filter diaphragm, with no concrete anti-seep collars, on all of its larger embankments. Sherard (1973) states that, "Even in small, homogeneous dams where no chimney drain is installed it is advisable to provide a drain and filter around the conduit at its downstream end for the purpose of intercepting concentrated leaks which follow the conduit."*

Rehabilitation of Deteriorated Conduits

Many small dams have been constructed over the past 30 years using corrugated metal pipe (CMP) spillways, and low hazard farm ponds which were once located in the middle of agricultural land have become focal points of new communities, often without benefit of needed renovation. With a design life of 15 to 35 years, these deteriorating CMP spillways are now presenting a costly dilemma for the current owners.

Conventional removal of the old conduit and replacement with a new pipe is expensive (much of the embankment needs to be removed, with excavation side slopes of 2(h):1(v) or flatter to minimize cracking and arching of the backfill), time consuming, and usually requires that the lake be drained during repair. If the CMP is not so severely deteriorated that internal erosion of the embankment material has occurred, then it is possible to "slipline" it with a smaller pipe (often made of plastic such as PVC or HDPE) and fill the annular space between the pipes with grout. The procedure has been used successfully on many dams and ponds over the past ten years.

It is important to consider the effect of the conduit repair on existing seepage in the embankment. Defects (leaks) in the existing conduit may have allowed seepage to enter the conduit undetected for many years. After installation of the slipliner and the annular space is grouted, the leaks are plugged and the seepage pattern may change. This can allow seepage to follow along the outside of the conduit until it reaches the downstream face of the dam. Without a properly designed filter the seepage may initiate internal erosion, which then can lead to dam failure. It is recommended that all sliplining repair projects include installation of a filter diaphragm around the conduit near the downstream end to control seepage and minimize the potential for internal erosion.



In the figure at right, the existing seepage pattern (white lines) entered the CMP conduit through defects in the pipe. After the CMP is sliplined and grouted, seepage into the pipe can no longer occur, and the seepage could find its way along the pipe to the downstream toe (black dashed lines.) A properly designed filter diaphragm around the conduit near the downstream end (light gray box) will intercept potential seepage and prevent internal erosion.

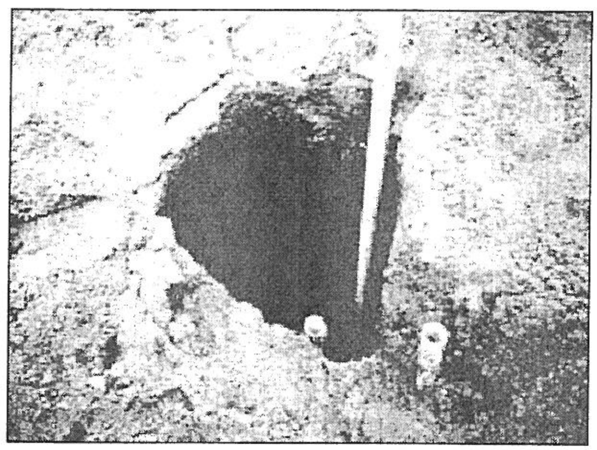
Consider Tin Cup Dam, which was constructed in Montana in 1906. The outlet works consisted of a rectangular masonry culvert in the dam foundation. Inspections of the dam in the 1990's noted sinkholes in the embankment fill along the conduit alignment, and in some places inspectors in the conduit could reach through open joints in the masonry without encountering the original backfill. The investigation concluded that repairs to the conduit were required. In 1997, the conduit was sliplined with HDPE pipe and the space between the liner and the masonry walls was to be filled with grout. (Note that the project took more grout than expected, and the contractor ran out of grout before all of the voids were filled). No filter diaphragm was installed. The following year, new seepage was observed along the outside of the spillway at the downstream end. The lake was immediately drained when it was concluded that the dam was in danger of imminent failure. (Luehring, Bezanson, and Grant 1999).

Conduit Installation in Dams
by Tunneling, Jacking and Boring, or Horizontal Directional Drilling

Tunneling, jacking and boring, and horizontal directional drilling (HDD) may have limited applicability to small, low hazard dams, but are not recommended for significant or high hazard dams. Difficulties exist with obtaining a watertight seal along the conduit and potentially with disturbing the embankment during installation. Until emerging technology and procedures are significantly improved and shown to be reliable, it is recommended that these renovation methods be restricted to installation of conduits in abutments and foundations, and to situations where traditional open cut excavation is not feasible.

There are a few isolated cases where drilling and jacking have been used to install pipes in dams. (Worster, Brown, Goertz and Shanklin, 2002, and Van Aller, 2003).

In testing of microtunneling and HDD for installation of pipes under levees, the US Army Corps of Engineers found that the process can severely damage the embankment (Bennett and Staheli, 1997). The pressures associated with pumping of the drilling slurry can cause hydraulic fracturing of the embankment and foundation soils.



In the photo at right, a very large surface void appeared directly above a test microtunneling installation when the operator stopped advancement of the machine but briefly allowed the slurry pump to continue to circulate the drilling mud. The void appeared in backfill surrounding some test instruments, some of which appeared to support the adjacent soils. (photo from Bennett and Staheli in CPAR GL-97-1).

Conclusions and Recommendations

Understanding the scenarios involving internal erosion is important in designing defensive measures to prevent these failures. Conduits through dams are of special concern because they are a discontinuity in an earth dam or foundation. Settlement above and adjacent to the conduit may be quite different from settlement in the rest of the dam. Soils may also be compacted differently around a conduit than for the rest of the embankment. These factors can cause cracking of the earth fill and other consequences. The contact area between a conduit and its surrounding earth fill and foundation is a potential pathway for seepage through the dam. Designers must consider the effect of the conduit and soil compaction around the conduit in their design to avoid possible problems and failures.

Most dam designers now recommend a zone of designed granular filter surrounding the penetrating conduit near the downstream end. This feature is termed a filter diaphragm. In many cases, the filter diaphragm is made an integral part of a chimney filter in the dam. Since filters have become a standard design element in dam designs, very few failures have occurred that can be attributed to internal erosion near conduits.

Finally, it is interesting to note that the NRCS national pond standard, "PS-378" has recently been revised. In the past, it required anti-seep collars for seepage control along conduits. However, in the latest version (NRCS 2002) it states that "***Seepage along pipes extending through the embankment shall be controlled by use of a drainage diaphragm, unless it is determined that anti-seep collars will adequately serve the purpose.***" After reviewing the numerous dam failures caused by seepage along the conduit over the past 50 years, it is hard to justify use of ineffective anti-seep collars. Hopefully, engineers who design dams and stormwater ponds will learn from our past mistakes and stop requiring anti-seep collars on conduits through dams.

FEMA will publish the "Conduits through Embankment Dams - Best Practices for Design, Problem Identification and Evaluation, Maintenance, and Repair" by the end of 2004. This document contains more detailed information than this brief summary.

I will place this paper and selected references on the Maryland Department of the Environment's "ftp" site, where it may be downloaded for about a month after this conference: ftp://ftp.mde.state.md.us/outgoing/Dam_Safety/ASDSO/.

References

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Most of these references (and dozens more) are included on the CDROM which will accompany publication of the "Conduits through Embankment Dams" manual.