VOLUME 1
ISSUE 1
MARCH 2013

Western Dam Engineering Technical Notes

A QUARTERLY PUBLICATION FOR WESTERN DAM ENGINEERS

WELCOME!

This is the inaugural issue of the ***Western Dam Engineering Technical Note***. This quarterly newsletter is meant as an educational resource tool for civil engineers who practice primarily in rural areas of western United States. This publication will present technical articles specific to the design, inspection, safety, and construction of small dams. This publication provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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The Western Dam Engineering Technical Note is sponsored by the following agencies:

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This news update was compiled, written, and edited by URS Corporation in Denver, Colorado.

Funding for the News Update has been provided by the FEMA National Dam Safety Act Assistance to States grant program.

Article Contributors (URS Corporation):
Jennifer Williams, PE; John France, PE; Jason Boomer, PE; Stan Ellis, PE

In this Issue

Simple Steps to Siphoning

Introduction

This article discusses a practical approach to the design and implementation of siphons – specifically applicable to small-dam owners and operators. Many older dams were not constructed with an outlet or other means of draining the reservoir. Lowering the reservoir may be needed for temporary construction or for emergency response. Siphons can be a low-cost means of providing a reservoir outlet if one does not exist.

Operational Theory

Siphons used in reservoir drawdown operate by atmospheric pressure pushing water over an obstacle (i.e., reservoir water over an embankment dam) and discharging on the other side at a lower elevation than the reservoir. In the same way a barometer works, atmospheric pressure pushes liquid up a siphon into the region of reduced pressure at the top/apex of the siphon. The region of reduced pressure at the top of the siphon is caused by liquid (water) falling on the exit side, creating a pressure differential. The maximum height, or lift, of a siphon is limited by the atmospheric pressure at the site. The height a siphon can lift water will, therefore, be lower for dams at higher elevations (for instance the western United States).

There are several parameters that must be evaluated when establishing the feasibility and design of a siphon. Bernoulli's equation can be applied to estimate a siphon's maximum lift, discharge capacity, diameter, and pressure.

Maximum Siphon Lift

The most critical parameter for a siphon at a given site is to determine whether it is hydraulically possible to 'push' the water the desired height over the dam or spillway crest. The required lift height can be determined by comparing the dam crest elevation (DCE) to the lowest desired reservoir water surface elevation (RWS); see Figure 1. At sea level, atmospheric pressure is generally 14.7 psi which is equivalent to a column of water about 34-ft high. Thus, 34 ft is the maximum theoretical height for a siphon. However, the maximum achievable lift is reduced by friction and other minor losses in the system due to velocity head. Therefore, it is good practice to assume that the maximum lift achievable by atmospheric pressure at sea level is equal to only about 20 to 25 ft of water. Atmospheric pressure can be assumed to decrease by about 4 percent (or 1 ft) for every 1,000-ft increase in elevation. Therefore, the maximum lift height of a siphon can be conservatively taken as:

$$H_{max} = 20' - \frac{RWS}{1,000}$$

Where H_{max} *= Maximum achievable siphon lift.*

RWS = Lowest desired reservoir water surface in feet of elevation

DCE = Dam crest in feet of elevation.

The maximum achievable siphon lift, H_{max}, must be greater than the value of (DCE – RWS). If the dam crest is too high compared to the desired reservoir-drawdown elevation, consider routing the siphon through a spillway or a temporary notch in the dam crest to reduce the required lift.

Predicted Siphon Discharge

Estimating the discharge capacity will help the designer

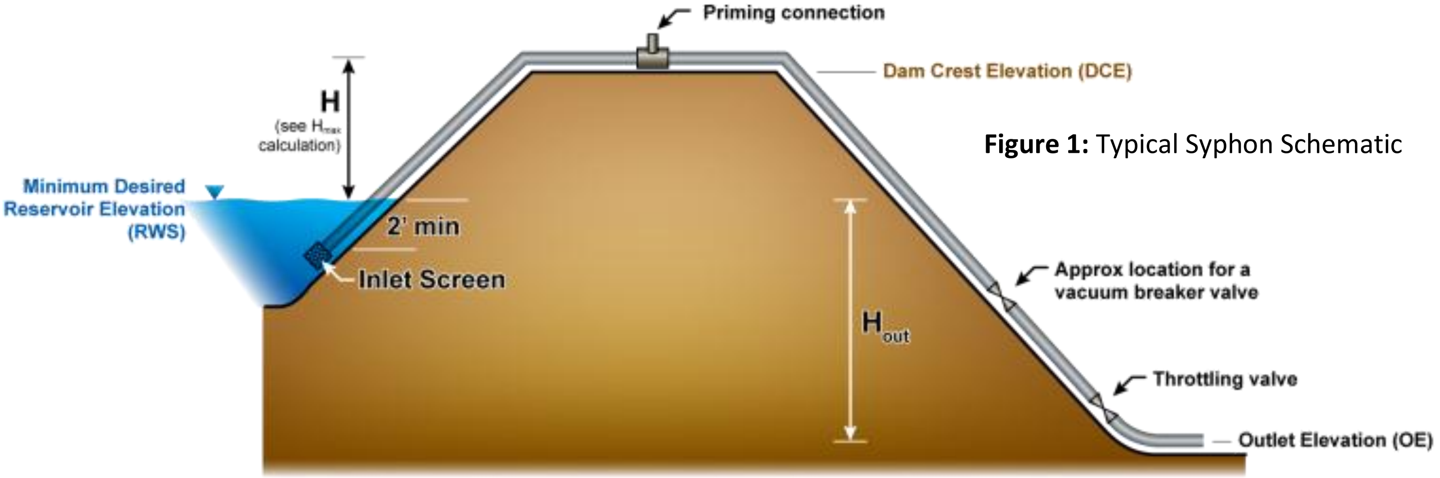

Figure 1: Typical Syphon Schematic

determine the size and number of siphon lines needed. Siphon discharge depends on the difference in elevation between the lowest desired reservoir elevation (RWS) and the elevation of the outlet (OE). Similar to the maximum lift, the discharge capacity is reduced by friction and hydraulic losses. The following variation of the Bernoulli Equation can be used:

$$Q = 0.0438D^{2.5}H_{out}{}^{0.5}(12fL + KD + D)^{-0.5}$$

$$f = 425\left({n^2}/{D^{0.33}}\right)$$

Q = flow in cubic feet per second
D = siphon diameter in inches
H_{out} = elevation difference in feet from the outlet to the lowest desired reservoir water surface (RWS-OE)
K = sum of dimensionless coefficients of hydraulic losses (entrance, bends, valves, exit, etc.). Typical values can be found in most hydraulic reference books
f= dimensionless friction factor
n = Manning's n for the pipe
L = total length of pipe in feet

System Pressure

Vacuum (negative) pressures of the system must be checked carefully to limit the risk of pipe collapse during operation. The lowest pressure often occurs at the apex of the siphon. However, the lowest pressure point can occur downstream of the apex. This occurs when friction and minor losses reduce the pressure in the outlet leg more than the decrease in elevation increases the pressure.

The equation to estimate pressure at the apex can be given as:

$$Y_A = -H - \frac{V^2}{2g}(1 + K' + fL'/D)$$

Y_A = Pressure Head (in feet) at the apex
H = Siphon Lift in feet (DCE – RWS)
K' = sum of minor loss coefficients between the RWS and apex
L' = length of pipe in feet upstream of the apex

CAUTION: The designer needs to evaluate pressures throughout the system to locate the lowest predicted pressure.

If the vacuum pressures are found to be too great for the preferred pipe material, a thicker-walled pipe and/or an air-vacuum breaker valve within the outlet leg will be required.

Design of Siphon Components

Siphon Layout and Valves: In order to help assure that the siphon runs full and that air does not enter and break the siphon through the discharge end of the outlet leg, it is important that the discharge velocity not exceed the inlet velocity. A practical way to help prevent this from happening is to keep the length of the outlet leg (distance from outlet to apex) greater than the length of the intake leg (distance from intake to apex). Another means is having the outlet leg be a smaller diameter than the inlet leg; however, this requires the use of a reducer which increases frictional losses and may reduce the achievable lift height. If needed, a vacuum-breaker valve can be designed and placed along the outlet leg, at an elevation below the lowest drawdown elevation of the reservoir.

It is often beneficial to place an air chamber at the siphon apex, where air will gradually accumulate and could be periodically released. This is particularly good practice for siphons expected to operate for long periods of time.

Intake: The intake needs to be submerged to avoid air entering the system and breaking the siphon. It should be placed a minimum of two feet below the lowest desired reservoir surface elevation to limit air entering through vortex action. Air entering will severely decrease efficiency and could break the siphon. A baffle (such as a piece of plywood or metal) can also be used over the mouth of the intake to limit the vortex.

Outlet: The discharge end of the siphon must be at a lower elevation than the lowest desired elevation of the reservoir. Ideally, it should be submerged to reduce the risk of air entrainment. Air entrainment could break the vacuum and immediately stop the flow. In many cases, submerging the outlet end is not practical. If the outlet discharges to the atmosphere, care should be taken to ensure the outlet pipe runs full, and valves be installed to release air at the apex as further described below. Additionally, if the discharge end is not submerged, precautions should be taken to ensure adequate erosion protection is provided or the discharge end is kept as far from the toe of the embankment as possible.

Pipe size and materials: The hose or pipe comprising the siphon can be constructed of a variety of materials (steel, PVC and HDPE are common), but must be free of kinks or obstructions and must have water-tight joints. Also the pipe should be designed with a wall thickness sufficient to prevent collapse due to negative pressures. Thin-walled plastic pipe and aluminum irrigation pipes are not recommended, because they are typically not strong enough to accommodate negative pressures in siphons.

Although there are no theoretical upper limits to the diameter of a siphon, economics and practicality usually dictate hose/pipe diameters in the range of ¾-inch to 30-inches, but commonly in the range of 2 to 8 inches. Additional siphoning capacity, if needed, is usually provided by more siphon pipes rather than by larger diameter pipes. Also, rather than having a single siphon and valves for conveying and controlling all of the water, it is often best to have several smaller-diameter siphons, with or without throttling valves – so that each can operate independently of the others.

Priming: The siphon must be primed (filled with water) or pumped in order to start the flow of water. Both ends of the siphon tube need to be closed to prime the siphon. A gate or butterfly valve can be used to close the ends of the pipe. This can then be used to control the flow during and after priming. There are two common methods for priming the siphon:

- Fill both the outlet leg and inlet leg of the siphon pipe with water through a fitting at the apex. The fitting must be large enough to allow air to escape as water fills the pipe (i.e. greater than the pump diameter). Place an airtight cap on the fitting when the pipe is full of water and open the discharge valve to begin the flow of water.
- Fill the longer outlet leg with water through a port at the apex. A vacuum pump can be used to draw air out and water in through the inlet side of the siphon. The apex port is then plugged and the discharge valve at the outlet opened to begin the flow of water.

Sometimes an intake valve is used to assist with priming, and, if needed, this valve needs to be opened before the discharge valve to start the flow of water.

Other Siphon Applications

Although this article focuses on the use of siphons for reservoir drawdown, siphons can also be used for dewatering applications during construction, as a means to pass additional inflows under major storm events, or a permanent means for withdrawing water on an on-demand need for reservoirs and canals. The theory and design considerations are the same as described above.

Conclusion

Siphons can, in the correct circumstances, provide a low(er)-cost alternative to drawdown a reservoir. The key operational parameters are: (1) the required hydraulic lift cannot exceed the effective local atmospheric pressure adjusted for vapor pressure and frictional losses; (2) the discharge point of the siphon must be lower in elevation than the body of water to be siphoned; and (3) the pipe or hose used for the siphon must be designed to withstand negative pressures.

Common Pitfalls in Siphoning:

- Ensure required lift height is feasible for site location and elevation [$(H_{max}>(DCE-RWS)$]
- Check pipe strength against collapse. Lowest pressure does not always occur at apex.
- Ensure outlet velocity does not exceed inlet leg velocity (use a longer outlet pipe length and/or smaller diameter pipe)
- Review need for vacuum break valves, throttling valves, and air chambers as described.

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- Reclamation - Central Arizona Project
- Lake Burnt Mills Dam Rehab

Low-Level Conduits – Rehab or Replace?

Introduction

Deterioration of low-level outlet conduits is a common problem, especially for older embankment dams. This article presents alternatives designers should consider prior to beginning a conduit replacement or rehabilitation project and a brief discussion of the potential pitfalls sometimes seen during the design and construction phases.

Rehabilitation or Replacement?

The first question the designer needs to ask is whether the conduit should be replaced or is a good candidate for rehabilitation. Conduit replacement is likely the approach providing the greatest reliability, but that approach will most likely require draining of the reservoir and be the highest cost option. In some cases, rehabilitation provides a reasonable alternative. Rehabilitation is typically accomplished by one of two methods, sliplining or cured-in-place pipe (CIPP) liners. Sliplining is completed by installing a smaller, "carrier pipe" into a larger "host pipe", grouting the annular space between the two pipes, and sealing the ends. A CIPP liner is a resin-saturated felt tube made of polyester, which produces a jointless, seamless, pipe-within-a-pipe. A CIPP liner is either inverted or pulled into the host pipe, cured-in-place using pressurized steam or hot water and serves as the new carrier pipe. Although these rehabilitation methods may also require draining of the reservoir, they are typically lower cost alternatives to full replacement. FEMA (2005) provides a detailed list of advantages and disadvantages of replacement and rehabilitation, which are summarized below.

Advantages of conduit replacement:

- Visual embankment/foundation evaluation after conduit removal.
- Allows repair of surrounding embankment that may have been damaged because of deteriorated condition of existing conduit.
- Allows for easy incorporation of filters designed according to the current state-of-practice.
- Potential for increasing the hydraulic capacity of the conduit.
- Conduit Replacement does not require specialty contractors, equipment or personnel.

Disadvantages of conduit replacement:

- Typically the highest cost alternative.
- Requires large open cut excavation through the embankment, which may put downstream areas at risk during construction.
- Potential for developing seepage paths at the contact between the unexcavated existing embankment and the replaced earthfill.

Advantages of conduit rehabilitation:

- Limited or no excavation required.
- Installation during weather conditions not suitable for replacement.
- It may be possible to maintain a full reservoir in some cases (i.e., conduit has upstream control and is accessible from downstream).
- Shortened construction schedule and reduced cost when compared to replacement.

Disadvantages to conduit rehabilitation:

- Not applicable for severely deteriorated conduits (i.e., conduits with severely compromised structural integrity, open joints or holes, pipe deformities, or conduits believed to have voids along the outside of the pipe). See Photo 1.
- Limitations for conduits with slight bends, deformities or non-uniform diameters.
- Most likely will require specialized contractors, and equipment for installation.
- May adversely affect seepage paths around the exterior of the existing conduit.

Additional advantages and disadvantages of the alternatives are also presented in “Technical Manual: Conduits through Embankment Dams,” produced by the Federal Emergency Management Agency (FEMA, 2005). The designer should consider both replacement and rehabilitation alternatives carefully and understand that each project site may have specific challenges that need to be considered.

Photo 1: Severely deteriorated CMP.[1]

Rehabilitation Alternatives

Of the two rehabilitation alternatives noted above, the more common option is sliplining (see Photo 2). High density polyethylene (HDPE) and properly coated steel pipe are the two most common pipes selected for sliplining rehabilitation and have similar design parameters. With little maintenance the service life of HDPE pipe can typically range between 50 and 100 years. Steel pipe requires provisions for adequate coating to provide similar levels of design life. Fiberglass reinforced pipe (FRP) and polyvinyl chloride (PVC) have also been used, but have drawbacks with regards to jointing (i.e., bell and spigot) and brittleness. Design considerations along with a comparison of HDPE pipe and coated steel pipe are summarized below.

Photo 2: Installing HDPE Liner pipe.[2]

<u>Existing Conduit Inspections</u>: It is important to complete a thorough cleaning and inspection of the existing conduit before moving forward with the design. For large diameter pipes the inspection can be completed visually by entering the pipe from either the downstream or upstream end, although confined space entry procedures should be followed. For small diameter pipes the inspection should be completed using a remote operated vehicle (ROV). The alignment (straightness) of the pipe, severity of deterioration, and location and dimensions of protrusions should be noted during the inspection.

<u>Size Selection</u>: When selecting the size and wall thickness of the carrier pipe, the designer needs to consider the hydraulic capacity, clearance from the existing pipe (annular space) including consideration of irregularities and protrusions, and the internal and external loadings. For large internal and external loadings, steel sliplining pipe may be required. The reduced diameter of the carrier pipe may not result in a reduced hydraulic capacity due to better hydraulic efficiency (lower friction losses) of the new carrier pipe. However, hydraulic capacity of the new carrier pipes needs to be checked against requirements.

<u>Seepage Paths</u>: After sliplining is complete the existing (host) pipe is essentially sealed. Depending on the severity of deterioration, the existing pipe may have been acting as a large drain for the embankment due to excessive seepage through the pipe/joints. Once the pipe is sealed, it is possible that phreatic levels in the embankment may increase, possibly increasing the potential for internal erosion (piping) along the conduit. To address this concern, the rehabilitation design should always consider adding a filter diaphragm near the downstream end of the pipe.

<u>Thermal Expansion</u>: In general, the sliplining pipe will be buried deep in the embankment and will experience limited temperature changes during the service life; however, the designer needs to understand the expansion and contraction limits of the selected pipe. Thermal expansion is not typically a large concern for steel pipe. However, if installed in very hot or very cold ambient air conditions, is it necessary to let the pipe reach equilibrium temperature before annular grouting.

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[1] Photo courtesy of www.cleanculverts.com

[2] Photo courtesy of www.hydroworld.com

Joints: When possible, pipe sections should be fabricated in the shop. However, there are several alternatives available for field connecting sections of both HDPE and steel pipe as described in FEMA (2005). Joint testing should be completed prior to grouting.

Flotation: Both HDPE and steel pipes will want to float during grouting and must be restrained physically by external “centralizers” between the host and carrier pipes or by filling the pipes with water or sandbags.

Inlet and Outlet Structures: Rehabilitation or replacement of inlets and outlets is an important consideration in the design of alternatives for an outlet rehabilitation project. The ability to fabricate and install carrier pipes to fit a given inlet structure configuration often drives the decision whether to utilize or replace an inlet structure. Similarly, the desire for retrofitting seepage collars or the need to repair the existing downstream slope or provide energy dissipation are considerations for outlets.

Grouting: Grouting the annular space between the new pipe and the existing pipe is essential (see Photo 3). Only contractor’s experienced in this type of grouting should be used for this specialized work. Typically grouting is completed from the downstream end with grout pumped to the upstream end through tremie pipes. Multiple tremie pipes of increasing lengths are used to inject grout and reduce the travel distance of the grout. Grouting should continue until the entire annular space has been filled and no voids remain. Vent/observation pipes are used to verify grout has filled the annular space. Securing bulkheads to contain the grout is also critical.

An in-situ alternative to sliplining is CIPP. This method is best suited for pipes that are not severely deteriorated, have limited to no protrusions, and have constant diameters. Many of the same design parameters should be considered. Curing of the carrier pipe is a critical step and one of two methods can be specified; pressurized steam, or pressurized hot water. Each has advantages and special consideration must be given to dry pipe installations versus where standing or flowing water will remain present within the host pipe during liner installation. Consultation with a CIPP manufacturer is highly recommended during the design process.

Photo 3: Grouting HDPE Liner pipe.[3]

Construction Considerations: Sliplining and CIPP pipe rehabilitation projects often involve working from one or both ends of the outlet with significant distance of pipe that cannot be accessed between. This introduces challenges during construction that must often be resolved in real time, i.e. once grouting or curing is started the effects cannot be reversed. For this reason adequate, experienced supervision is essential during critical activities such as liner installation and grouting. Additionally, experience has shown the value of “mini” preconstruction meetings involving all field personnel just prior to the start of those critical activities. A discussion “what if’s” is a key component of those meetings to determine who makes necessary field decisions and what range of decisions might be needed to ensure project success.

Conclusion

This article provides a short summary of the design parameters and construction issues to consider during design of an existing conduit rehabilitation project. Before proceeding with a rehabilitation project, the design should answer the following questions.

Should I replace the existing conduit or rehabilitate it in place?

- Conduits that are severely deteriorated or possibly have voids adjacent to the conduit due to internal erosion should be replaced. A detailed cleaning and internal conduit inspection should be

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[3] Photo courtesy of www.water.state.co.us

completed prior to selecting replacement or rehabilitation.

Which in-situ rehabilitation method should I select?

- A designer should evaluate both sliplining and CIPP for any rehabilitation project. The advantages and disadvantages of each alternative should be carefully evaluated for each specific site.
- An HDPE carrier pipe is a cost effective alternative for small-diameter conduits requiring a flexible pipe that is subjected to minor to nominal external and internal loadings. HDPE pipe may also be preferred in highly corrosive environments.
- A CIPP liner provides similar benefits to that of HDPE sliplining, but requires the use of a specialty contractor
- A steel carrier pipe may be the preferred choice for straight host pipes with larger diameters and nominal to high internal and external loadings.

Common Pitfalls in Sliplining:

- Suitable grout mix to grout full length of annulus
- Avoid pipe damage during construction. Inspect and repair any that occurs.
- Use experienced contractors
- Consider any potential reduction in capacity

FEMA's technical manuals provide detailed discussion of parameters that should be considered during the sliplining design process.

FEMA - Conduits through Embankment Dams

FEMA - Plastic Pipe Used in Embankment Dams

References

The following is a list of design references that should be used during design:

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Filter Design and Construction Considerations

Introduction

This article is intended to provide practical guidance for use by dam owners and engineers for the design and construction of filters for embankment dams, particularly small embankment dams. This article is not intended to be an all-inclusive guide for design of filter and drain systems. In many instances, the article directs readers to other references that provide more detailed information. In addition, an extensive list of references on the topic is provided at the end of this article.

Why Filters?

Although there are many existing dams that were constructed without filters and which have performed satisfactorily, filters offer substantial benefits with respect to dam safety.

A well-designed filter provides protection against possible defects in an embankment core. If a core contains pervious layers or through-going transverse cracks, a filter (commonly referred to as a chimney filter) will safely collect seepage through these defects and prevent piping of the core, as illustrated in Figure 1.

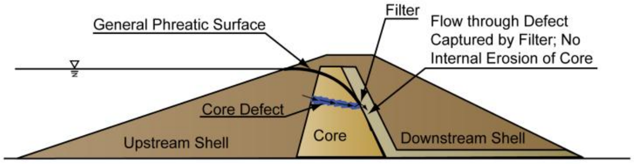

Figure 1: Filter collecting flow through core defect.

Filters placed around conduits or other structural penetrations (commonly referred to as filter diaphragms) also provide protection against internal erosion or piping along the exterior walls of the penetration, where seepage is most likely to occur. Filters installed around conduits or structural penetrations should always include an outlet to prevent water pressure from building up in the filter, as shown in Figure 2.

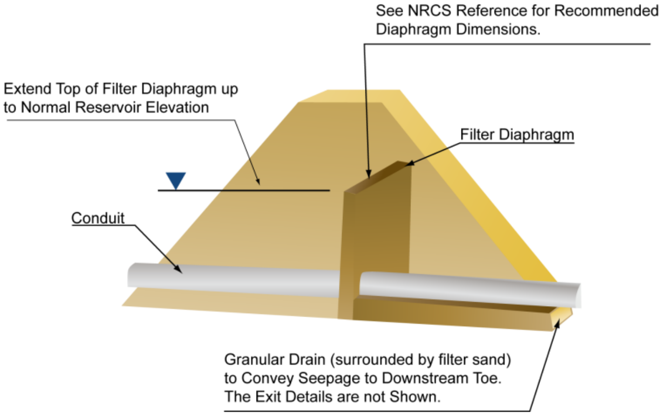

Figure 2: Filter diaphragm surrounding conduit.

Additional benefits for incorporating a filter include:

- Well-designed chimney filters provide positive control to produce a phreatic surface that is well within the embankment, improving stability.
- Dam safety risk analyses have shown that a well-designed filter provides substantial benefits in risk reduction.

Specifically, it is recommended that filters be included in all of the following cases:

- All new dams over 25 feet high.
- Existing dams with evidence of seepage above the toe on the downstream face.
- Existing dams with likely defects through the core.
- Existing dams in seismic areas with the likelihood of cracking under seismic loading.
- Outlet works replacements or rehabilitations for existing dams.

Now that we understand the importance of filters in embankment dams, let's discuss some of the considerations that should be included during design.

30% of all dam failures have been attributed to seepage or piping that could have likely been averted by a proper filter

Designing Embankment Filters

Three of the most important factors to consider during the design of an embankment filter are gradation, location, and size/thickness. The material gradation of the filter is important to ensure filter compatibility requirements are met for surrounding materials and to prevent piping or internal erosion of the embankment. The location of the filter is important to ensure it is effectively lowering embankment phreatic levels and protecting the critical zones of the embankment. The size or thickness of the filter zone is important to ensure it meets necessary capacity requirements and also provides ample thickness to assure continuity during placement and to prevent contamination during construction.

Let's focus first on the filter gradation design. Detailed guidance documents for gradation design for soil filters are readily available from three federal agencies: the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) [NRCS (1994)]; the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) [Reclamation (2007)]; and the U.S. Army Corps of Engineers (USACE) [USACE (2004b)]. This article does not include a repetition of the detailed guidance included in the three documents referenced above, all of which are readily available. Rather, this article presents a general discussion of the NRCS method, highlighting some of the important practical aspects of the guidance.

The NRCS method for filter gradation design is summarized in 11 steps. The 11 eleven steps are not reiterated in this article; however a brief discussion presenting the goals of the various steps is provided below.

Steps 1 through 5 of the procedure establish the criteria that must be met to provide a filter that will prevent movement of soil particles from the base soil (the soil being protected) into the filter – the filter function. Mathematical regrading of the base soil is performed in these steps and is a critical part of the filter design process.

Step 6 establishes criteria to assure that the filter is significantly higher in permeability (hydraulic conductivity) than the base soil – the drainage function.

Steps 7 and 8 are intended to prevent the filter from being gap graded. A gap graded filter is a soil composed of particles of two different gradation ranges, e,g, gravel and fine sand, with very little if any of the intermediate grain sizes, e.g. coarse and medium sand. Gap graded soils can be internally unstable; that is the coarse fraction does not serve as a filter to the fine fraction, and the fine fraction can be eroded out through the coarse fraction.

Steps 9 through 10 are intended to produce a filter gradation that will limit the likelihood of particle size segregation during placement of the filter. Segregation of the filter into coarser and finer zones can result in coarse zones which do not provide the required filter function.

If a particular design does not require that the filter meet permeability requirements, the permeability criterion, Step 5, can be relaxed, as long as the filter criterion, the gap graded criteria, and the segregation criteria are met. An example of where this might apply would be a filter for a core, with a very permeable, filter-compatible shell downstream of the filter. In this case, the downstream shell would serve the drainage (permeability) function, lowering the phreatic surface immediately downstream of the filter.

If it is typically desired that the filter has high permeability (hydraulic conductivity),it is recommended that the filters have less than 3% nonplastic fines (material finer than the No. 200 sieve size), in place, before compaction, and at most 5% nonplastic fines, in place, after compaction. Permeability of the filter decreases dramatically as the fines content increases above these levels.

It is very rare to find a case where natural materials can satisfactorily serve as filters, without significant processing. Natural materials are typically not suitable as filters for the following reasons:

- The required gradations requirements for filters are relatively narrow, and the variation in gradations in natural deposits is typically too great to be confident that all of the material obtained from a natural source will be within the specified narrow limits.
- It is generally desirable for filters to have very low fines contents, less than 3 to 5 percent, as discussed above. It is very unusual to find natural deposits that reliably have such low fines contents.
- Natural deposits often have enough coarse particles that they do not meet the filter requirements to prevent segregation during placement.

It is not necessary that the exact gradation limits resulting from the filter calculations be used in the project specifications. Rather, the calculated gradations can be used to select and specify readily-available, commercially-produced aggregates. Use of readily available materials can significantly reduce project costs. It is very unusual when readily-available commercial materials cannot be found to meet filter requirements. Typical readily-available commercial materials include ASTM, AASHTO, and state transportation department standard gradations. After the required filter gradations are calculated, gradations of readily-available materials should be reviewed for compliance. The availability of local suppliers producing the desired gradations should be verified before the gradations are specified.

For most mixtures of sands, silts, and clays found in dams and foundations, ASTM C33 fine aggregate will meet filter requirements. Although, ASTM C33 fine aggregate is a suitable filter for a wide range of soils, the filter calculations should always be completed for the particular base soils being protected, to verify the suitability of the specified filter. If ASTM C-33 fine aggregate is suitable as a filter, then ASTM coarse aggregate gradation No. 8, AASHTO coarse aggregate gradation No. 8, or a similar transportation department specification is a suitable, filter-compatible drain material.

If a drain pipe is included in the filter and drain system, the slots or perforations in the pipe must be sized to be filter-compatible with the soil material that surrounds the pipe. The guidelines published by the three federal agencies referenced above provide criteria for appropriately sizing pipe slots or perforations, although there are some variations among the three documents in this regard.

Currently, the guidelines and policies of the principal federal agencies involved in dam design, construction, and operation indicate that geotextiles are not to be used for critical filter functions in dams and at locations that could not be relatively easily accessed for replacement. This includes geocomposite drains in lieu of sand filters. This is due to the potential for geotextiles to clog over time, be damaged during installation, or deteriorate over time. Clogging can lead to increased pore pressures within the dam, which may be unacceptable. Damage or deterioration could compromise filter function.

For zoned embankments the chimney filter should be located immediately downstream of the core. In recent years the application of risk analysis to dam seepage issues has led many practitioners to design chimney filters that extend up to an elevation equal to the normal pool. Based on the potential for cracking and dispersion, filters may be extended to the flood pool level or even the dam crest.

Now let's look at some items to consider during construction of the embankment filter.

Constructing Embankment Filters

In design of a chimney filter drain, analyses are normally completed to determine the thickness of the filter and drain zones required to convey the estimated seepage flow rates. Normally these calculations result in relatively thin filter and drain zones and layers. In reality, the design thicknesses of the filter and drain layers are normally controlled by consideration of constructability, not seepage flow capacity requirements. In considering constructability, the designer must address the question of how thick must each zone be to ensure that the zone is continuous, with no interruptions. In typical filter and drain construction, the filter and drain materials are delivered to the dam in dump trucks and moved into the final location by loaders, dozers, or graders, after which they are compacted. Placement of chimney drains using this methodology is subject to what has been called the "Christmas tree effect." This effect can result in portions of the filter not meeting the minimum specified thicknesses. As discussed earlier in this article, filter and drain materials are most commonly commercially-produced, processed materials, and, therefore, are expensive. As a result, there are always pressures to reduce the thicknesses of these materials and reduce cost. It is essential to resist any pressures to reduce filter and drain zone thicknesses to dimensions less than those that will reasonably assure satisfactory construction.

Photo 1: "Christmas Tree" Effect

The NRCS provides minimum sizes for embankment filters; however, the following recommendations should also be considered:

- Inclined filter and drain zones which will be constructed at the same time as adjacent upstream and downstream zones should be designed with a minimum horizontal dimension of 5 feet.
- Vertical filter and drain zones which will be constructed at the same time as adjacent upstream and downstream zones should be designed with a minimum horizontal dimension of 3 feet.
- Inclined filter and drain zones which will be constructed against an excavated face should be designed with a minimum horizontal dimension of 3 feet.
- Horizontal filter and drain zones should be designed with a minimum thickness of 1 foot.

Filter and drain materials are not particularly amenable to conventional earthwork compaction density control. Typical filter sand materials do not exhibit the “standard” compaction curve shape, with a clear maximum dry density and optimum moisture content. Rather, these materials exhibit their maximum dry densities when either completely dry or nearly saturated. Drain materials are typically uniform gravels, which are not suitable for conventional compaction testing or conventional field density testing. Conventional end product compaction specifications (e.g. percent compaction specifications) have sometimes been used for filter and drain materials, however, they are difficult to apply in the field, for the reasons given above.

End product compaction specifications based on relative density requirements have also sometimes been used. However, the relative density test is notoriously difficult to apply in the field. For most applications, it is desired that the filter and drain materials be compacted sufficiently to provide sufficient strength and to limit settlement. In locations subject to significant seismic loading, it is also necessary that the filter material be sufficiently dense to resist liquefaction if it is saturated. All of these requirements can be met by achieving densities that are greater than 70 percent relative density, which is not particularly difficult to accomplish with these clean materials. Further, it is desirable not to overcompact the filter material, because this can lead to excessive particle breakage and increased fines content, which is not desirable.

In general, it is easier to use a method specification for filter and drain materials, in which minimum compaction equipment and minimum compaction effort (e.g. number of coverages with the equipment) are specified. In addition to the compaction equipment and effort, it is also recommended that the placement specification for the filter include thoroughly wetting the material (to near saturation) as it is being compacted. There are a number of practical ways to accomplish this, including 1) covering the material with a water truck immediately ahead of the compactor, 2) applying water to the material with a hose immediately ahead of the compactor, and 3) mounting a water spreader bar on the compactor ahead of the compaction drum. Vibratory compaction equipment is the most appropriate equipment for compacting filter and drain materials. A method specification requires close QC inspection during the work to assure that the method is being followed, but it is generally the easiest approach to use for these materials. If desired, the method specification can be combined with verification of the method by density testing in the initial production placements or in a test section.

It is important to prevent contamination of the filter and drain materials during construction. To perform their functions as intended, the filter and drain materials must contain very limited amounts of fine materials. Contamination can occur if runoff carries fine-grained material into the filter and drain materials. To prevent contamination, it is recommended that filter and drain materials be maintained at least one lift higher than the adjacent materials that contain fine-grained soils, and the adjacent materials should be sloped slightly to drain away from the filter and drain materials. Should the filter or drain materials become contaminated despite efforts to prevent contamination, the contaminated materials should be removed and replaced.

Conclusion

Several guidance documents are available to assist the designer in developing a well-designed filter for an embankment dam. The designer must carefully consider both the design parameters and also the construction considerations during the design process.

Common Pitfalls in Filter Design/Construction:

- Check filter compatibility!
- Avoid geotextiles
- Provide sufficient width for constructability
- Extend to a suitable height in the embankment
- Filter all penetrations through the embankment

References

To aid the designer through the process, the following is a list of design references that can be used during design:

- URS (2010), “Technical Note 4: Chimney Filter/Drain Design and Construction Considerations,” Montana Department of Natural Resources, Dam Safety Program, December.
- NRCS (1994), "Gradation Design of Sand and Gravel Filters," U.S. Department of Agriculture, Natural Resources Conservation Service, National Engineering Handbook, Part 633, Chapter 26, Washington, DC, October.
- NRCS (2007), "Filter Diaphragms," U.S. Department of Agriculture, Natural Resources Conservation Service, National Engineering Handbook, Part 628, Chapter 45, Washington, DC, January.
- Reclamation (2007), “Design Standards No. 13: Embankment Dams,” Chapter 5 – Protective Filters, U.S. Department of Interior, Bureau of Reclamation, Technical Service Center, Denver, CO.
- FEMA (2005), Technical Manual: Conduits through Embankment Dams, FEMA 484, Federal Emergency Management Agency, September.
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- Talbot, James and Mark Pabst (2006), “Filters for Earth Dams, Gradation Design and Construction Guidance Used by Federal Agencies,” ASDSO Journal of Dam Safety, pp. 13-24, Winter 2006.
- U.S. Army Corps of Engineers (1993), Manual EM 1110-2-1901, Seepage Control, Appendix D, Filter Design, U.S. Army Corps of Engineers, September 30, 1986, revised April.
- USACE (2004), EM 1110-2-2300, General Design and Construction Considerations for Earth and Rock-Fill Dams, Appendix B, Filter Design, U.S. Army Corps of Engineers, July.

Links to Key Reference Documents

NRCS - Chapter 26: Gradation Design of Sand and Gravel Filters

NRCS - Chapter 45: Filter Diaphragms

FEMA - Filters for Embankment Dams

FEMA - Conduits through Embankment Dams

Reclamation - Chapter 5: Protective Filters