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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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- Colorado Division of Water Resources
- Montana Department of Natural Resources
- Wyoming State Engineer's Office

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GOOD TO KNOW:

Valuable Low-Cost Reference:
The Embankment Dam Reference Toolbox provides a comprehensive collection of design standards and references for dam engineering available from ASDSO.

Upcoming ASDSO Webinar Dam Safety Training:

- *Tolerable Risk Guidelines for Dams, How Safe is Safe Enough?, by David S. Bowles, Ph.D., P.E., April 9, 2013*
- *Loss of Life Consequence Assessment for Dam Failure Scenarios, by Wayne J. Graham, P.E., May 14, 2013*

ASDSO Training Website

Other Upcoming Training Opportunities:
Best Practices for Inspection, Maintenance, and Repair of Small to Medium Size Dams

In this Issue

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.

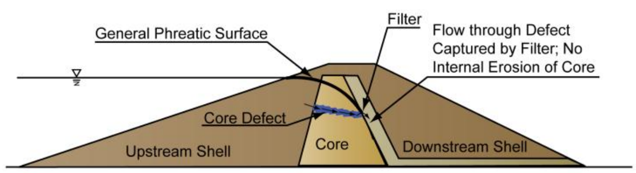

Figure 1: Filter collecting flow through core defect.

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.

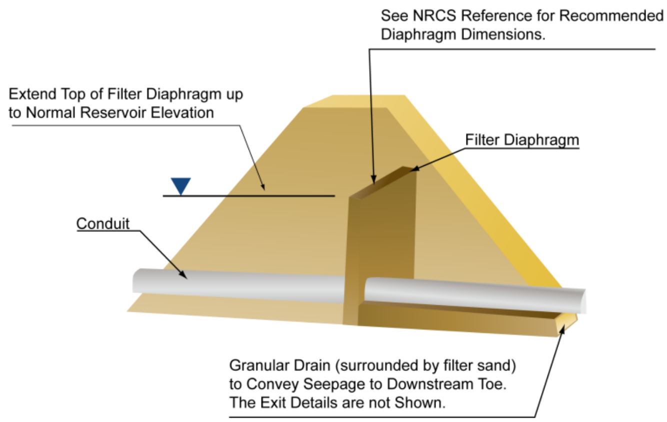

Figure 2: Filter diaphragm surrounding conduit.

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.
- FEMA (2007), Plastic Pipe Used in Embankment Dams, FEMA P-675, Federal Emergency Management Agency, November.
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- France, John W. (2004), "Seepage Collection and Control Systems: The Devil is in the Details," ASDSO Annual Conference.
- Hammer, David P. (2003), "Construction of Vertical and Inclined Sand Drains in Embankment Dams, ASDSO Annual Conference, Minneapolis, MN.
- McCook, Danny K. (1997), "Chimney Filters – Design and Construction Considerations." ASDSO Annual Conference, Pittsburgh, PA.
- McCook, Danny K. (2003), "The Filter Design Tightrope," ASDSO Annual Conference, Minneapolis, MN.
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- Sherard, J.L., L.P. Dunnigan, and J.R. Talbot (1989), "Critical Filters for Impervious Soils," ASCE, Journal of Geotechnical Engineering Division, No. 115(7), pp. 927-947, July.
- 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