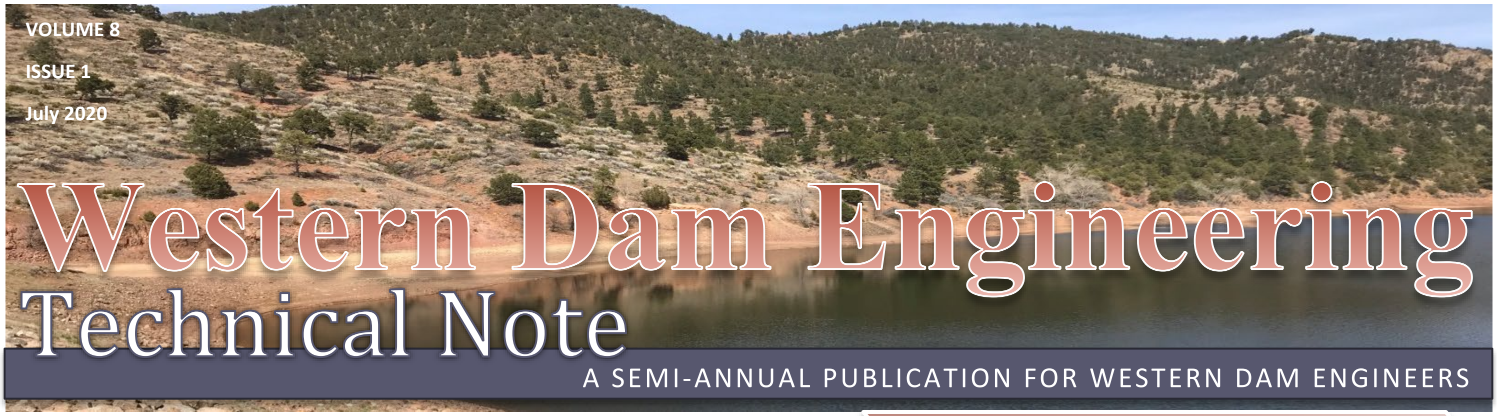

VOLUME 8
ISSUE 1
July 2020

Western Dam Engineering Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **rehabilitation after an internal erosion incident** and **dewatering for construction projects** . This newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to small and medium dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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

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

This Technical Note was compiled, written, and edited by AECOM in Denver, CO

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

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Upcoming ASDSO Webinar Dam Safety Training:

- **Low-Level Conduits – What Can Go Wrong, How to Inspect, How to Repair?** *August 11, 2020*
- **Delhi Dam – A Compound Failure,** *October 13, 2020*

Upcoming Virtual Classroom Technical Seminars

- **Inspection and Assessment of Dams**, *Nashville, TN, August 4-6, 2020*
- **HEC-RAS 2D**, *Chicago, IL, October 27-29, 2020*

Upcoming Conferences

- **Dam Safety 2020**, *Virtual Conference, Sept. 21-25, 2020*
- **Southeast Regional**, *Charleston, SC, Dec. 7-10, 2020*

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In this Issue

Assessment and Rehabilitation Following an Internal Erosion Incident

By: Jennifer Williams, PE; Jessie Drayton, PE; and Elliott Drumright, PE.

Introduction

Compared to other embankment dam failure modes such as slope stability or overtopping, internal erosion can often progress much further and cause significant damage within the dam or foundation before obvious signs of embankment distress are visible on the surface. Several steps must occur during the development of an internal erosion failure mode; often thought of as initiation, continuation, progression, and finally breach development steps. Identifying internal erosion early in the development process may allow for more cost-effective intervention measures before additional damage is sustained during later progression phases of the failure mode. Understanding the conditions that occur during the progression stages is also critical to evaluating repair alternatives when internal erosion conditions have advanced. This article discusses how to evaluate the extent of damage that has occurred due to internal erosion through understanding typical internal erosion event trees. The focus is on assessing the need and appropriateness of long-term rehabilitation measures to bring the dam back into service. Emergency intervention for failure modes rapidly advancing toward potential breach is not discussed in this article. For more information on emergency intervention for internal erosion, refer to "Thinking Fast – Emergency Response to Seepage and Internal Erosion" in the May 2017 *Western Dam Engineering Technical Note [1]*.

Potential Failure Modes (PFMs)

Effective intervention for suspected internal erosion requires identification of the potential failure mode(s) at work within or beneath the embankment. The typical failure modes specific to internal erosion include (see also Figures 2 through 4):

- Internal Erosion through the Embankment
- Internal Erosion through the Foundation
- Internal Erosion of the Embankment into the Foundation
- Internal Erosion into/out of a Conduit or Drain
- Internal Erosion along the Outside of a Conduit
- Concentrated Leak Erosion at Contact with the Embankment Foundation or a Structure

Identifying the PFM can help inform the internal erosion mechanism and pathway to determine where the damage may have occurred or is occurring. Refer to "Internal Erosion: Issues Just Below the Surface" in the August 2015 *Western Dam Engineering Technical Note* [2] for more detailed descriptions of the mechanics of internal erosion processes for embankment dams.

Event trees separate the conditions and steps necessary for a PFM to lead to failure. They can help in identifying where internal erosion may be occurring, the extent of damage that may have occurred, and if localized repair would be sufficient or if the damage has spread such that larger scale repairs are required. Figure 1 shows a typical event tree for an internal erosion failure mode and the following sections discuss the event tree nodes in more detail.

- Reservoir Loading (at or above threshold level)
  - Flaw exists-Continuous crack, high permeability zone, zones subject to hydraulic fracture, etc.
    - Initiation-Particle detachment (erosion starts)
      - Continuation-Unfiltered or inadequately filtered exit exists
        - Progression-Continuous stable roof and/or sidewalls
          - Progression-Constriction or upstream zone fails to limit flows
            - Progression – No self-healing by upstream zone
              - Unsuccessful detection and intervention
                - Dam breaches (uncontrolled release of reservoir

Figure 1: Event Tree for Internal Erosion

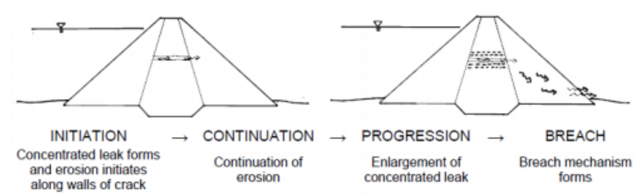

Figure 2: Internal Erosion through the Embankment PFM Nodes [3]

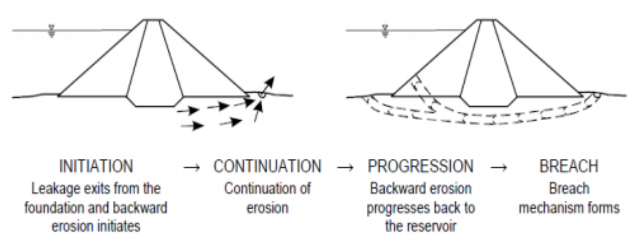

Figure 3: Internal Erosion through the Foundation PFM Nodes [3]

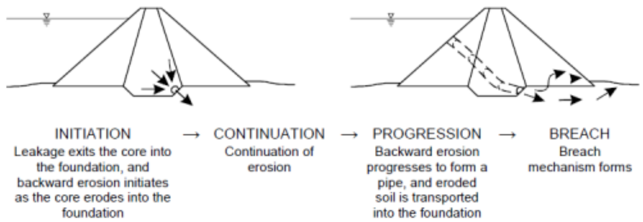

Figure 4: Internal Erosion of Embankment into Foundation PFM Nodes [3]

Reservoir Level

The reservoir level represents the hydraulic loading and influences the phreatic level and pore pressures within the embankment dam and foundation. All dams experience seepage due to the hydraulic loading. As long as the phreatic surface and piezometric pressures remain at levels anticipated in the design, and soil particles are not being eroded due to the seepage flow, no adverse effects are expected. In some cases, seepage may only be evident when the reservoir is at or above a threshold level, and the observational skills and logbook of the dam operator are important in identifying when conditions at a particular dam are atypical.

Initiation

Initiation of internal erosion occurs when conditions exist that allow soil particles to be transported out of the embankment or foundation by seepage flow. In general, homogeneous earthen embankments without any interior zoning or drainage features (toe drains, chimney or blanket drains) and/or with limited or no construction documentation of fill placement are susceptible to internal erosion. Erosion may be due to the presence of soil in the foundation or embankment that is erodible under the seepage conditions, usually non-cohesive soils. Erosion may also be due to a flaw that exists that facilitates concentrated seepage flow and scour of the erosion. The flaw can be due to the natural characteristics of the soil or rock at the dam, poor design, construction techniques or an issue that has developed over time during operations.

Surface expressions at this phase are subtle and may include wet areas, sand boils, or sediment being collected in toe drains or other seepage collection systems including ditches, collections channels, or weirs.

Continuation

Transportation of dam material continues in cases where there is no downstream filter, whether engineered or accidental. Thus, soil particles continue to be transported out of the embankment or foundation by seepage flow. Potential damage that may have occurred at this stage is likely still internal with a potential increase in the size of the flaw that allowed initiation to occur. More voids or zones of loose material have likely formed as more material has been transported out of the dam. Other than sand boils at the downstream toe, surface expressions such as depressions or slumping of the slope or whirlpools in the reservoir may still not be visible at this phase.

Progression

Once material begins to be transported from the dam and foundation, the void that forms can enlarge, eventually progressing toward a dam failure. As the void enlarges soil particles continue to be transported out of the embankment or foundation in increasing quantities and increasing seepage flow. Erosional damage to the interior of the dam is likely significant at this point and worsening at an ever-increasing rate.

Identification and Early Intervention

Initiation

This is the most difficult stage of erosion to assess and identify, as the signs are often subtle. Developing conditions may occur for many years without significant indicators. But recognition of the signs of initiation provides opportunity for early intervention activities that may be significantly less expensive and extensive, and more likely to be successful than if the internal erosion is allowed to progress. All dams seep and making a confident decision about whether seepage that is occurring is detrimental requires a detailed evaluation to understand the embankment and foundation conditions and evaluating if those conditions are susceptible to damaging erosion.

A study of construction documents, field investigations and past performance records should be used to evaluate the likelihood flaws or zones susceptible to internal erosion may be present. Bureau of Reclamation and U.S. Army Corps of Engineers developed a publicly available document that assists in this evaluation: Internal Erosion Risks for Embankments and Foundations [4].

A semi-quantitative risk analysis could also be performed to develop a better understanding of the most likely causes of the internal erosion and focus monitoring and future intervention actions accordingly. Refer to "Risky Business - Introduction to Dam Safety Risk Assessment" in the April 2018 issue of the *Western Dam Engineering Technical Note* [5] for more information on how to conduct such an analysis. Sharing this information with the dam tender or operator is key to developing judgement as to the significance of visible seepage or observed changes to increase the likelihood that potential signs of initiation would be caught during regular monitoring activities.

One indicator is cloudiness (turbidity) of seepage water at the downstream toe or around penetrations (e.g., conduits). Collecting seepage flow in a clean and clear container may help in identifying fine soil particles. A seepage exit point that is increasing in size or volume may also be an indicator. Small sand boils may also be visible if the exit point of the seepage happens to be clearly visible. If internal erosion of the embankment into the foundation or internal erosion of the foundation is occurring, such indicators may not be visible at the dam toe as the seepage flow might not appear at the surface until a distance downstream.

If initiation is identified, repairs should focus on preventing continuation and progression of the erosion from occurring once the mechanism and pathway of the erosion is well understood. Common repairs include sealing upstream entry locations, providing adequate filter protection for the seepage exit areas, and establishing focused monitoring programs for signs of additional movement of soil. Measures to address the flaw within the dam that led to initiation should also be considered. This often requires more extensive rehabilitation. A risk analysis can help decision makers evaluate warrants of more extensive repairs.

Continuation

A soil zone that acts as an effective filter for the eroding material can arrest most internal erosion failure mechanisms. The dam and foundation zones should be evaluated for their effectiveness to serve as a filter by evaluating filter compatibility of adjacent zones. The evaluation primarily consists of comparing material gradation of adjacent soils. If construction data of in place material is not well documented, field investigations may be needed to collect and test physical samples.

Procedures for evaluating filter compatibility are well studied and documented. One such procedure is published by NRCS and available online: Gradation Design of Sand and Gravel Filters [6]. The NRCS filter procedure was developed as guidance for design of new filters. Although it can be applied to evaluate if existing filters meet the same criteria, an alternate procedure was developed by Foster and Fell to evaluate effectiveness of filters that do not meet modern design criteria: Assessing Embankment Dam Filters That Do Not Satisfy Design Criteria [7]. The latter procedure by Foster and Fell is the more commonly applied procedure for existing, older dams.

Turbidity or cloudiness of seepage flow is an indication that continuation is occurring especially if the quantity of seepage or turbidity is increasing (assuming a similar reservoir level as prior). More frequent and/or increased size of sand boils are also indications.

Potential repairs for erosion that has continued due to lack of filter may be similar to those described for addressing known initiation and often focus on establishing a filtered exit for the seepage pathway. Constructability limitations often lead engineers to prefer a filter/berm overlay applied to the downstream embankment face or exit. However, if the eroding material is migrating through coarse, open-work material with large void space, a filter at the exit of the coarse zone may not be effective. The coarse zone may be able to store enough of the eroding material to cause significant damage or even failure of the embankment, making the downstream-face filter moot. In this instance, rehabilitation becomes more extensive.

Progression

Dam operators and engineers are more likely to recognize that the internal erosion is worsening at this stage in the failure mode event tree as signs of embankment distress become more visible on the surface. These may include increase in settlement; depressions or sink holes on the embankment face;

expanding sand boils; rapid increase in downstream seepage flow; or a whirlpool in the reservoir.

Intervention needs to be rapid, coordinated, and thorough at this stage to avoid progression to full failure. By this stage in the failure mode event tree, damage has occurred along the seepage pathway and repairs likely require more comprehensive reconstruction to bring the dam back to design service. More significant repairs include reconstructing portions of the embankment and/or foundation to remove flawed and damaged areas and installing a cutoff wall to block the seepage path or constructing a seepage berm to filter and collect seepage exiting the downstream embankment slope.

Long-Term Repairs

Methods to mitigate internal erosion in embankment dams include one or a combination of the following:

1. Seepage control measures – such as internal filters/drains, toe drains, downstream drainage trenches, relief wells, horizontal drains, drainage galleries and conduit filter diaphragms to collect or direct the seepage into engineered features that provide effective filtering and drainage.
2. Seepage reduction measures - such as cutoff walls or upstream-slope geomembranes to reduce the amount of seepage by lengthening or reducing the permeability of the seepage path, thus reducing the gradient and quantity of flow.

The type of repair that is appropriate for a given dam depends on the type of internal erosion and primary path of seepage. Seepage control measures generally address the continuation node of the event tree in that they provide filtered drainage of seepage. Seepage control measures are most effective when applied downstream of the dam or core centerline. Seepage reduction measures generally address the initiation node of the event tree in that they reduce seepage gradient and flow velocity. Seepage reduction measures are most effective when applied upstream of, or at, the dam or core centerline. Figure 5 shows locations and orientations of potential design features to mitigate internal erosion. Numerous redundancies are depicted in the figure and it should not be implied that all such measures would be warranted. However, because of the potential for flaws within any constructed seepage cutoff feature, a filtered exit should always be incorporated in a comprehensive repair.

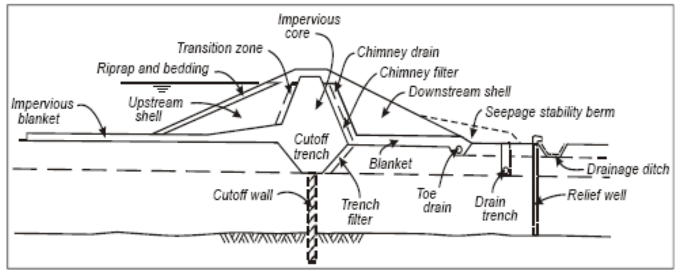

Figure 5: Potential Seepage and Internal Erosion Mitigation Features

This section provides broad guidance for design of seepage mitigation measures as a means of an introduction to various alternatives that can be considered. Selection and design of rehabilitation, from minor repair to comprehensive reconstruction, is site and condition specific, requires specialized study and analyses, and should be developed by a licensed engineer specializing in dam safety design. An experienced contractor and field supervision are also mandatory.

Seepage through the Embankment

Filters: Filters are seepage control measures that can vary widely in configuration, location, and extent. Filters can be constructed as an addition to the downstream toe or slope for mitigation of homogenous embankments, which will limit disturbance to the existing embankment and may only require limited reservoir drawdown. Configuration of downstream filter overlays will depend on the seepage location, volume, and pressures. Where filtering of adjacent zones within the embankment is required, removal and replacement of part of the embankment will allow a filtered chimney drain to be installed, typically connected to a blanket or toe drain for safe conveyance to the toe. Filters should typically be constructed as two-stage systems with a finer-graded filter, and a coarser-graded drain. See "Filter Design and Construction Considerations" in the March 2013 *Western Dam Engineering Technical Note* [8] for general filter design considerations.

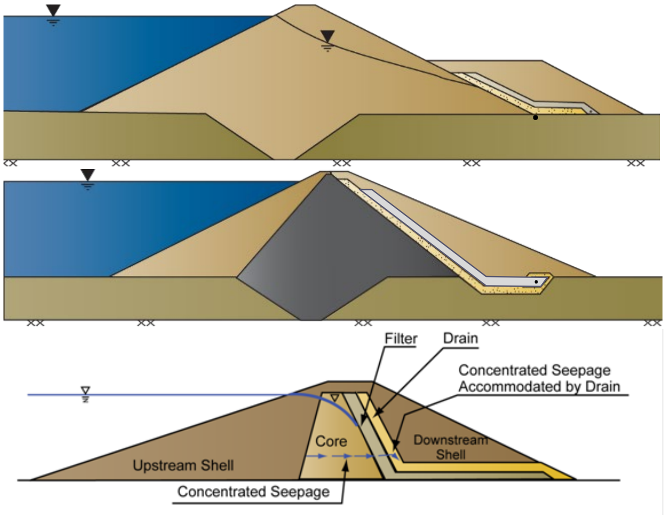

Figure 6: Potential Embankment Filter Configurations

Cutoff Walls: Cutoff walls are seepage reduction measures that can be constructed through the embankment and into the foundation to lengthen the seepage path. Cutoff walls can be constructed by backfilling a deep narrow trench with concrete, self-hardening slurry, or other low permeability backfill; driving sheet piles; drilling contiguous (secant) concrete piles; or soil mixing columns. To be effective the wall must be deep enough to significantly increase the seepage path length and ideally terminate in low permeable overburden or bedrock. Ensuring that the cutoff wall is constructed with no windows or flaws that could provide a seepage path through the wall is vital to its success.

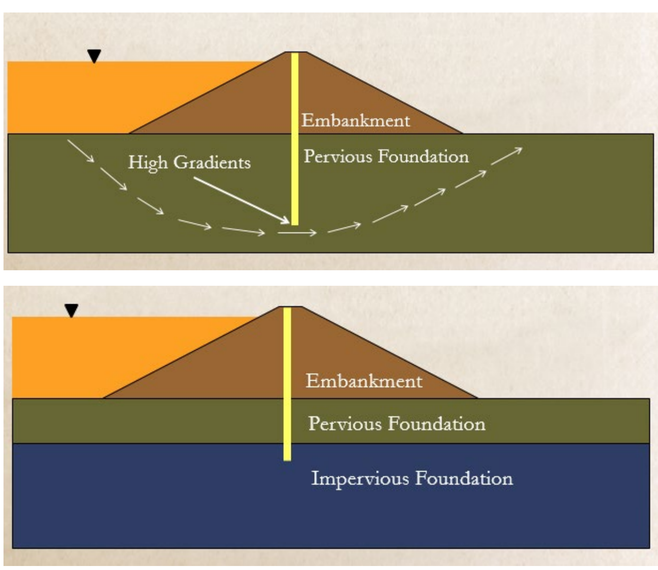

Figure 7: Potential Cutoff Wall Configuration

Upstream Slope Liner: Another alternative to reduce seepage flow through the embankment is installation of a low-permeable liner on the upstream face. Typical liner materials include concrete facing, geosynthetic membrane, asphalt liner, or clay blanket. The liner reduces seepage at its entrance point and requires lowering of the reservoir. Use of a geomembrane would require additional inspection and maintenance on a regular basis and full replacement from time to time.

Seepage into or through the Foundation

Filters: Filters can be used to control seepage through the foundation by providing a filtered exit. However, ensuring that the filter covers the critical exit points might be more difficult as foundation seepage exits may be further downstream and more difficult to identify than exit points from the embankment, particularly for jointed rock foundations.

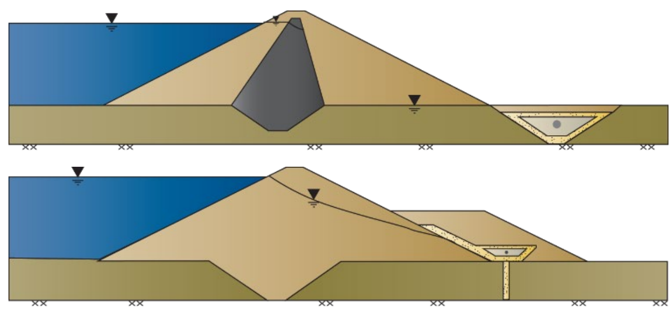

Figure 8: Potential Foundation Filter Configurations

Cutoff Walls: Cutoff walls can be used to reduce seepage through the foundation by lengthening the seepage path. To be effective the wall must be deep enough to significantly increase the seepage path length and ideally terminate in a low-permeable soil or rock layer that is not prone to erosion, cracks, or solutioning. Options for constructing a cutoff wall through the foundation are similar as those listed for through the embankment. One exception may be sheet piles if the wall needs to penetrate into bedrock. Again, ensuring that the cutoff wall is constructed in a way that no windows or flaws exist that could provide a seepage path through the wall is vital to its success.

Upstream Blanket: If draining of the reservoir is possible, a blanket that extends upstream from the toe of the dam can be effective in reducing seepage through the foundation by lengthening the seepage path at the entrance point. The blanket can be constructed of low permeability soil or a geomembrane.

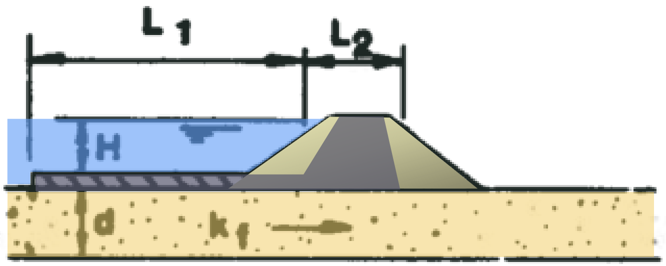

Figure 9: Upstream Blanket Configuration

Grouting: Installing a grout curtain or closing windows in an existing curtain can reduce seepage exiting through the foundation. A thorough understanding of the embankment and foundation conditions are needed to adequately design and implement grouting to prevent fracturing the embankment or foundation.

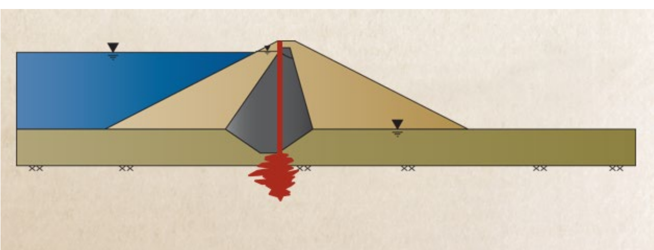

Figure 10: Foundation Grouting from the Dam Crest

Relief Wells: Mitigating high foundation pressures which may rupture a confining layer and cause high seepage gradients can be achieved with a system of relief wells. These well points are drilled into high-permeable layers to relieve excess water pressure. Their effectiveness is limited to the drawdown perimeter of the well and therefore it typically requires numerous wells to be effective for a given site. Filtering is required along with the relief well to avoid transportation of soil. Relief wells also require regular maintenance to mitigate clogging.

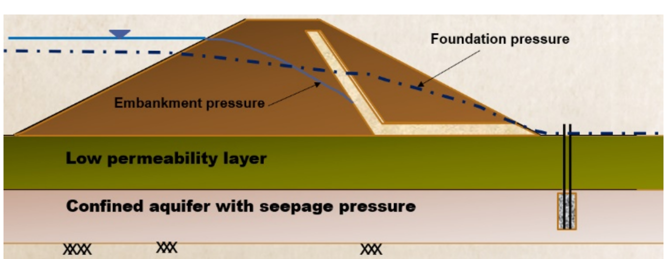

Figure 11: Relief Well Schematic

Seepage into, out of, or along a Conduit

Conduit Lining: Deteriorating conduits that develop open joints or corrosion holes may result in seepage and internal erosion into or out of the conduit, depending on the pressure conditions within the conduit and adjacent soils. Sliplining conduits to seal cracks and voids and to restore structural integrity of a deteriorating conduit can be achieved using several alternative materials, including using an HDPE or steel carrier pipe grouted within the host pipe or using cured-in-place polypropylene liners. The reduction in outlet flowrate due to the reduced inside diameter of the conduit must be accounted for in the design. Lining the conduit would cut off seepage paths into or out of the conduit but would not reduce or control seepage occurring along the conduit. See the following *Western Dam Engineering Technical Note* articles for more information on conduit rehabilitation:

- "Low-Level Conduits – Rehab or Replace?" March 2013 *Western Dam Engineering Technical Note* [9]
- "You Down with CIPP? Yeah! You Know Me"' May 2016 *Western Dam Engineering Technical Note* [10]
- "Cellular Grout Use in Conduit Sliplining" [11] and "Mechanical Seals for Conduit Repair" [12] both in the August 2017 *Western Dam Engineering Technical Note*.

Downstream Filter Diaphragm: If the conduit is in good condition but seepage is occurring along its alignment, a filter diaphragm can be installed along the downstream portion of the conduit to provide a filtered exit. Some removal and replacement of the downstream slope or toe around the conduit may be necessary. It may also be necessary to remove a portion of the conduit as it is important to extend the filter diaphragm below the conduit invert. The filter diaphragm needs to have adequate soil cover to prevent blowout and/or provide sufficient drainage out of the diaphragm. Guidance documents for designing filter diaphragms are available online: Filter Diaphragms (NRCS) [13] and Technical Manual: Conduits through Embankment Dams [14].

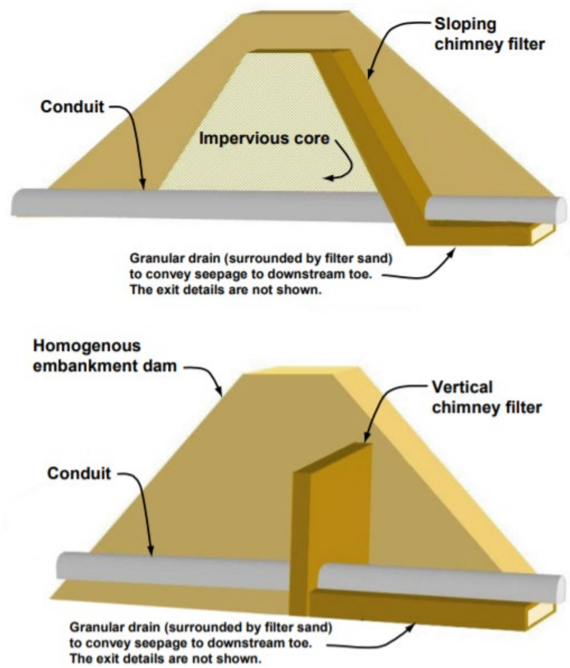

Figure 12: Conduit Filter Protection

Conduit Replacement: For conduits with more serious corrosion issues, replacement may be the required option, which requires removal and replacement of at least a portion of the embankment. A new conduit would address cracks or corrosion holes which may have resulted in seepage into or out of the original conduit, as well as allow for proper compaction around the conduit and placement of a filter diaphragm to address potential erosion along the conduit. The filter diaphragm needs to extend across the full width of the embankment excavation, crossing over the cutslope, or be integrated into the embankment chimney filter. If appropriate given the dam configuration, the existing conduit could be abandoned in place. See "Abandonment of Low-Level Outlet Conduits, Think It Through before You Grout It Through" in the August 2018 *Western Dam Engineering Technical Note* [15] for more information on conduit abandonment.

Seepage along a Foundation or Structural Contact

Reconstructed Interfaces: At the contact of earthen backfill with hard features (i.e., spillway walls, intake structures, buried conduits, foundation bedrock), inadequate compaction, arching, or differential settlement can lead to gaps at the contact, resulting in increased seepage and the potential for internal erosion. If the contact surface is vertical, the interface can be reconstructed to provide a battered or stepped surface for better compaction of the earthen material. Filters can also be placed at the contact to reduce the potential for internal erosion.

Conclusion

Internal erosion presents a dam safety concern that when identified early, can often be effectively addressed in a timely and resource-efficient manner. However, if the internal erosion goes undetected, long-term repairs can be costly and disruptive to operations. Properly identifying the potential failure modes at a dam that could lead to internal erosion can help improve the probability that early signs of seepage and internal erosion are recognized during regular maintenance and dam surveillance.

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[10] *Western Dam Engineering Technical Note*. Volume 4, Issue 1, "You Down with CIPP? Yeah! You Know Me!," May 2016.

[11] *Western Dam Engineering Technical Note*. Volume 5, Issue 2, "Cellular Grout Use in Conduit Sliplining," August 2017.

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How Dewatering Can Derail Construction Projects

By: G. Richard Bird, PE; Jessie Drayton, PE; Gregg Batchelder Adams, PE; and John W. France, PE, DGE, DWRE

Introduction

Construction dewatering can be a critical aspect of dam construction or rehabilitation, with regard to both schedule and safety. For new dam construction, dewatering is often required for excavations into alluvial riverbed soils. For dam rehabilitation or repair, dewatering is sometimes required for excavations to construct seepage collection systems, appurtenant structure modifications (e.g., outlet works extensions) or condition modifications (e.g., remove liquefiable soils). In both cases, successful dewatering is critical to construction schedules and construction quality. In the case of dam rehabilitation, dewatering can also be critical to dam safety if a full or significant reservoir pool is maintained during construction. Ineffective or inadequate dewatering can lead to serious construction delays, safety risks and increased cost. This article presents the key topics of consideration for dewatering systems for dam rehabilitation projects. A large portion of the content of this article is taken from the authors' presentation and publication of this topic as part of the 2017 USSD Annual Conference and Exhibition proceedings [1].

Purpose of Dewatering

Construction below ambient groundwater levels for new dams or dam rehabilitation should not be attempted without adequate control of groundwater and subsurface hydrostatic pressures. The purpose of dewatering systems is to facilitate construction of subsurface structures and features below ambient groundwater levels. A properly designed and implemented dewatering system will:

- Prevent heave, uplift, and blowout
- Prevent internal erosion of soils
- Intercept seepage that would otherwise emerge from the slopes or at the bottoms of excavations
- Increase stability of excavated slopes by lowering pore water pressures
- Improve excavation and backfill characteristics of sandy soils
- Reduce lateral loads on excavation support systems, if they are used

Designing a dewatering system is not a precise science. Trial and error and adaptation of the system in the field are often required. The originally designed and installed dewatering system is not always sufficient, and adjustments must be made based on observed performance. Success of a dewatering system is not only dependent on analysis, but also on practical experience and adaptation to actual conditions. Dewatering efforts should be directed by an appropriately experienced person. This person may not necessarily be an engineer. Superintendents and technicians employed by dewatering companies often have excellent practical experience that may be immensely valuable in implementing and adapting dewatering systems. It is recommended that during preparation of construction specifications the designer consult individuals with practical experience in dewatering. However, where dewatering is critical, the final design should be performed by a licensed engineer with at least 10 years of experience designing dewatering systems for many projects of similar complexity in similar geological conditions. Figure 1 is an example of an excavation that would be considered critical if the reservoir had not been drawn down before the excavation was started.

Figure 2 - Uncontrolled downstream seepage exiting with reservoir down to deadpool, rehabilitation of headworks, Lake Frances Dam, MT (Note pin boils near toe; the two wells were ineffective). (Courtesy of Montana Department of Natural Resources and Conservation)

Design Responsibility

Both contractor-designed and engineer/owner-designed dewatering systems can be successful. Typically, the designer has studied the site extensively and likely understands the site conditions and their relationship to dewatering better than the contractor can be expected to understand them in the short period allowed for preparation of a bid. Therefore, it is incumbent on the engineer to impart his or her knowledge to the greatest degree practical.

There are some circumstances when it is reasonable and prudent for the owner/engineer to take on the responsibility of designing the dewatering system. Factors and possible scenarios that could lead an owner/engineer to take on the responsibility of designing the dewatering system include:

- The dewatering system performance is critical to public safety.
- The dewatering system performance is schedule critical—there is no time for extensive trial and error in implementation of the dewatering system.
- Subsurface conditions are complex; contractors may be tempted at bid time to omit dewatering a deeper pervious layer that requires pressure relief for bottom stability of the excavation.
- The successful prime contractor bids the project using a dewatering subcontractor proposal that is inadequate and is reluctant to increase the scope of dewatering beyond that included in the subcontractor's bid, or the contractor and dewatering contractor select an overly expensive system to reduce risk.
- The successful prime contractor gets no bids from competent, responsible dewatering subcontractors at bid time and estimates the cost of dewatering using his own opinion of the required dewatering scope.
- An engineer/owner designed system provides a basis to bid for contractors and, therefore, removes most of the uncertainty from this bid item, which is typically highly variable, thus potentially reducing claims.

These considerations are summarized in the following table.

Who Should Design Dewatering System?		
Issue / Condition	Design Responsibility	
	Engineer	Contractor
Schedule-Critical Project	X	
Dewatering Critical for Public Safety	X	
Comprehensive Subsurface Data, Including Aquifer Testing		X
Complex Subsurface Conditions	X	
Deep Pressure Relief Required to Prevent Blowout	X	X
Extensive, Well-documented Prior Dewatering Experience at Site		X

If it is ultimately decided that the dewatering system will be contractor-designed, the specifications should be as explicit as possible regarding dewatering requirements. If wells, wellpoints, or other special measures are believed to be necessary, then this should be clearly stated in the specifications. In all cases, performance requirements should be clearly identified—e.g., "piezometric heads shall be lowered to at least *X* feet below the bottom of the excavation, as demonstrated with piezometers, and the system shall be designed assuming that the reservoir elevation can rise a maximum of *Y* feet during construction."

Dewatering Methods

Powers et al. [3], has a comprehensive discussion comparing the effectiveness of various dewatering methods in varying conditions.

Sumps and Ditches

The use of sumps and ditches for dewatering is generally most effective for limited dewatering in soil and rock strata that are not easily erodible, such as clean gravels and clean sandy gravels. Sumps and ditches will be most effective if there is limited or no recharge. This method is generally inadvisable for pervious and semi-pervious (silty sand, silt) soils with recharge where the groundwater must be lowered by more than a few feet. However, there have been some exceptions to the limitation of a few feet of drawdown for sumps and ditches. With highly engineered, partially penetrating sheet pile cofferdams or other barriers, adequate interior berms to extend the seepage paths from the source of seepage to the sump/ditch system, maintenance of uniform excavation slopes and placement of filters at and below exiting seepage on the excavation slopes, sumps, and ditches have been used to lower groundwater tens of feet in relatively clean sand on some major projects [2].

Sumps can range from relatively simple to more complex installations, as shown in Figures 2, 3, and 4. Sumps must be designed and constructed to prevent internal erosion of surrounding soils. This requires properly sizing openings in the sump pit structures and may also require installation of properly graded filter and drainage aggregates (clean sands and gravels) around the sumps.

Limitations of sump and ditch installations include:

- Drainage can be relatively slow in sand and gravel soils with high fines contents.
- Wet conditions can remain during excavation and backfilling.
- Sumps and ditches require space within the excavation and can increase the excavation footprint.
- Workers skilled in construction and operation of sumps and pumps are required to provide enough water control and prevent internal erosion.

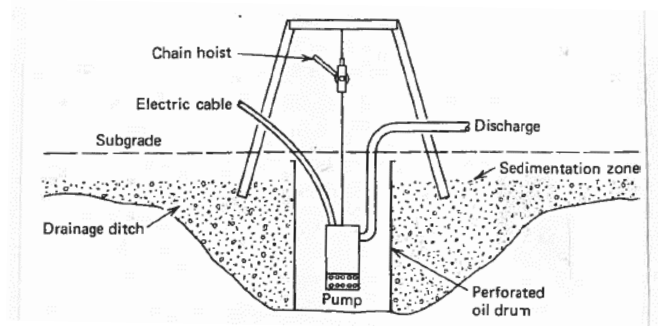


Figure 2 - Example of Simple Sump Installation [3]

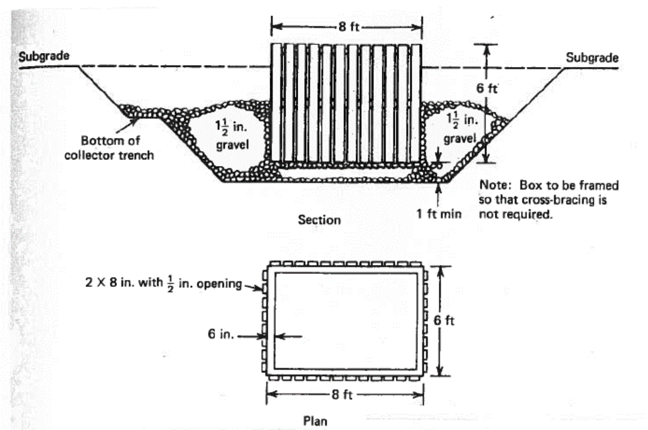


Figure 3: Example of More Complex Sump Installation [3]

Figure 4 - Example of well-designed sump to collect both surface water and groundwater at Nevada Dam, MT (Courtesy Montana Department of Natural Resources and Conservation)

Wellpoints

Figure 5 - Wellpoint system along trench excavation, Lake Frances Dam Outlet Works Rehabilitation, MT (Courtesy Montana Department of Natural Resources and Conservation)

Wellpoints (Figure 5) are versatile and are appropriate for soils with a wide range of permeability. A wellpoint system consists of individual wellpoints in the ground connected with a vacuum manifold or (header pipe) to a suction type pumping system on the ground surface. A single stage wellpoint system at sea level can typically produce no more than 15 feet of drawdown below the wellpoint pump suction elevation. This limit for drawdown per wellpoint stage should be decreased for higher elevations (e.g., 9 feet per stage for ground elevation of 5,000 feet above sea level). Drawdowns exceeding 15 feet require additional lower stages of wellpoints. By definition, a dewatering wellpoint includes a drawdown pipe so that water entering the wellpoint screen above the bottom of the drawdown pipe is forced to flow downward in the annulus between the drawdown pipe and the wellpoint screen. Wellpoints are typically installed in rings or lines, with center-to-center spacing varying from 3 feet to 25 feet. Screens, meshes, and/or geotextiles are included in each wellpoint to prevent infiltration of surrounding soils during pumping, and a select sand filter is placed in the annulus between the wellpoint and the drilled or jetted hole in which it is installed. Wellpoints are typically 3 inches or less in diameter. Wellpoints are usually jetted in place, and hydraulic fracture of the adjacent materials could occur using this method, which could damage a foundation for a dam or appurtenant structure. When there is a question, drilling without fluids (e.g., sonic and hollow stem auger methods) should be used to install wellpoints. There are two types of wellpoints typically used for construction dewatering: eductor wellpoints and vacuum wellpoints.

An *eductor wellpoint* consists of a conventional dewatering wellpoint that is attached to the suction of a concentric pipe (as opposed to a twin pipe) eductor, shown on Figure 6 below. With an eductor well or wellpoint, vacuum can be developed for the full length of the filter above the eductor, if the eductor breaks suction *and* if the air flow to the filter is sufficiently low. Eductor systems can lower the groundwater level as much as 100 feet below the top of the excavation. Because eductor pumps are inefficient (typically 30 to 35 percent), these systems work best in situations where the volume of pumped water per wellpoint is less than about 2 gallons per minute. An additional drawback of an eductor system is that the air and water flow capacity is limited to the total capacity of the eductor. If too much air enters the filter or well screen, it will not be possible to maintain a reasonably high vacuum in the filter. An alternative to eductors when water flows are higher than 2 gallons per minute or when air flow is too high to maintain a vacuum in the filter is a sealed deep well system (discussed below) with applied vacuum.

As shown on Figure 6, eductors are often used to pump small diameter deep wells when individual well flows are small. Commercially available 4-inch parallel pipe eductors will fit in 4-inch inside diameter well casings.

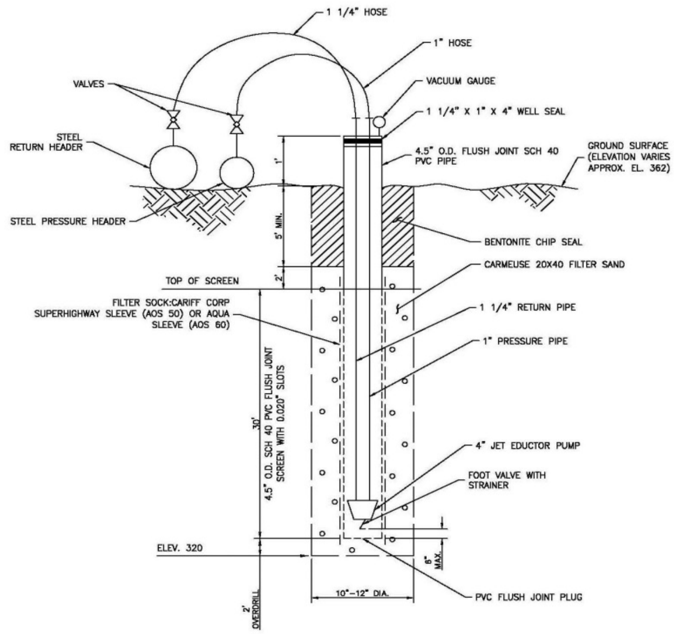


Figure 6 - Typical Design Detail for an Eductor Well (AECOM Technical Services)

Deep Wells

Deep wells consist of well casings extending below foundation bottom excavation with submersible or lineshaft turbine pumps installed inside the well casings, as shown on Figure 7. The deep wells need to be large enough in diameter to accommodate pumps that can provide sufficient capacity, which will be a function of the specific subsurface conditions at the site.

Deep wells are usually most suitable in moderate to high permeability soils, where the slope of the cone of depression is relatively flat and the effect of the individual deep well is felt at significance distance from the well location. Large flows can be accommodated using high capacity pumps. In the right conditions, deep wells can lower the groundwater hundreds of feet. Deep wells installed around the periphery of an excavation can provide pre-drainage for the full depth of the excavation. However, there are circumstances, as discussed below, where the deep well system alone may not be enough to provide adequate pre-drainage.

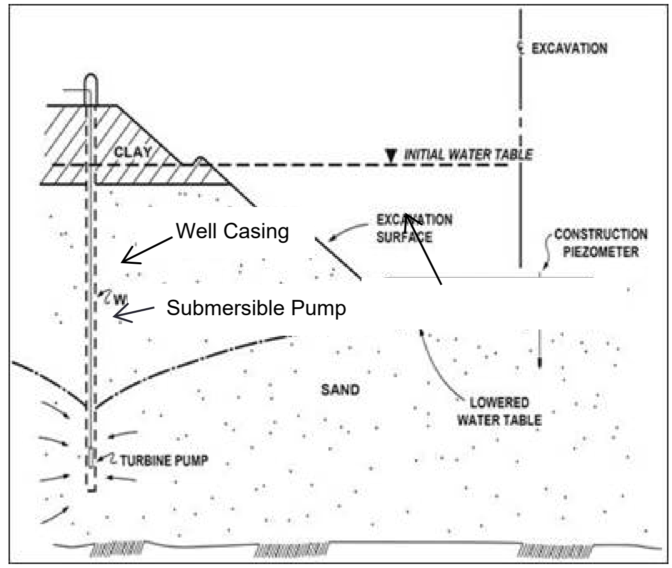


Figure 7 - A Deep Well Installation (Adapted from [5])

A cone of depression develops around a pumped deep well. If a relatively low permeability boundary exists near the bottom of the excavation, as illustrated on Figure 7, the collection capacity of the deep wells is limited by the submergence of the well screen when the system is pumped. If the submergence[1] is marginal or inadequate, supplemental dewatering within the excavation may be required to achieve the required drawdown, also as shown on Figure 7.

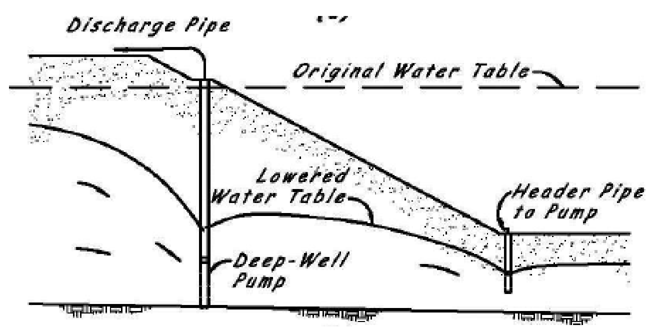


Figure 8 - Supplemental Dewatering Required If Low Permeability Boundary Exists Near Bottom of Excavation [4]

[1] Submergence is defined as the distance between the groundwater level at the well and an impervious layer below the bottom of the well screen when the groundwater level has been lowered by the dewatering system. It is impractical to lower the phreatic level closer than about 4 feet above the top of a laterally extensive horizontal impervious stratum in or underlying the pervious stratum being dewatered.

Deep wells can also be adapted to dewatering fine-grained soils, like those dewatered using high vacuum wellpoints and eductor wellpoints, by sealing the annulus of each deep well above the filter pack and applying a vacuum to the well casing. The well is pumped using a low capacity submersible pump, the casing is sealed against the discharge pipe and pump cable using a compression-type well seal. The smallest commercially available submersible pump has a capacity of about 2 to 3 gallons per minute. Since the steady flow to the well in fine soils is likely to be below the pump capacity, automatic level controls are used to cause the pump to operate cyclically. Provided the number of starts per day is less than the motor manufacturer's criteria, the pump and motor will be covered by the manufacturer's warranty. Vacuum is applied to the wells using electrically driven vacuum pumps installed at the ground surface. The only limit to the lift that can be achieved is the head capacity of the submersible pump that is selected. In many cases, deep wells with applied vacuum will be more economical to install and operate than a comparable eductor well system, and the air handling capacity can be increased, if necessary, either by changing the vacuum pump capacity or increasing the number of vacuum pumps connected to the well system.

Drainage Trenches with Perforated Collector Pipes

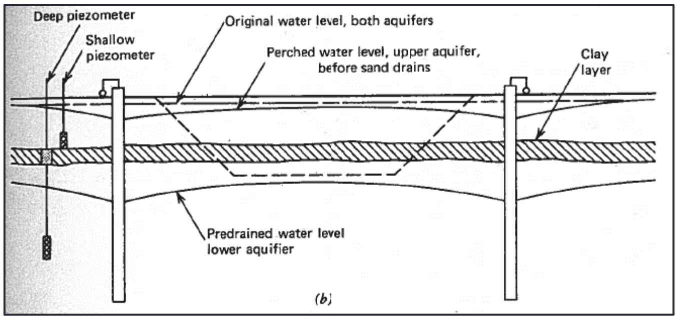
Drainage trenches with perforated collector pipes have been used to dewater excavations for constructing pipelines and other linear structures. The pipes are typically wrapped in a geotextile and installed with specially equipped trenchers, as shown on Figure 9. The pipes installed through this method are connected to a wellpoint pump at the ground surface or a submersible pump in a vertical or inclined riser connected to the horizontal perforated collector pipe.

Figure 9 - Trench and Collector Pipe Installation (Courtesy of DeWind Trenching)

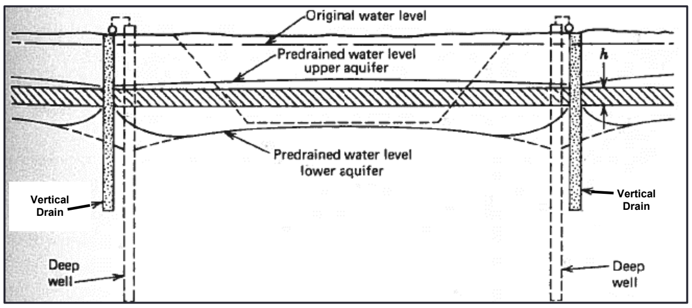
Vertical Drains

Vertical drains can be effective in dewatering perched groundwater in semi-pervious (silty sand or silt) or pervious strata overlying hydraulically isolated pervious strata with adequate submergence for well or wellpoint screens. The vertical drains intercept seepage in the upper stratum and conduct it to the lower dewatered stratum. Historically, vertical drains consisted of sand columns, called sand drains; however, in the past few decades, manmade wick drains or earthquake drains, (see Figure 10), have become the more common technology for vertical drains. The potential effectiveness of vertical drains is illustrated on Figure 11.

Figure 10 - Installation of Earthquake Drain by Hollow Mandrel Advanced with Vibratory Hammer (Courtesy of Hayward-Baker Inc.)



a) Without vertical drains.



b) With vertical drains.

Figure 11 - Potential Effectiveness of Vertical Drains [2]

Electro-osmosis

In low permeability clays and silts, electro-osmosis can be used for dewatering. An electrical current is established in the soil using a system of electrodes. Water migrates from the positive electrodes (anodes) to the negative electrodes (cathodes). The cathodes serve as wellpoints where the migrating water can be extracted. An electro-osmosis system is illustrated on Figure 12.

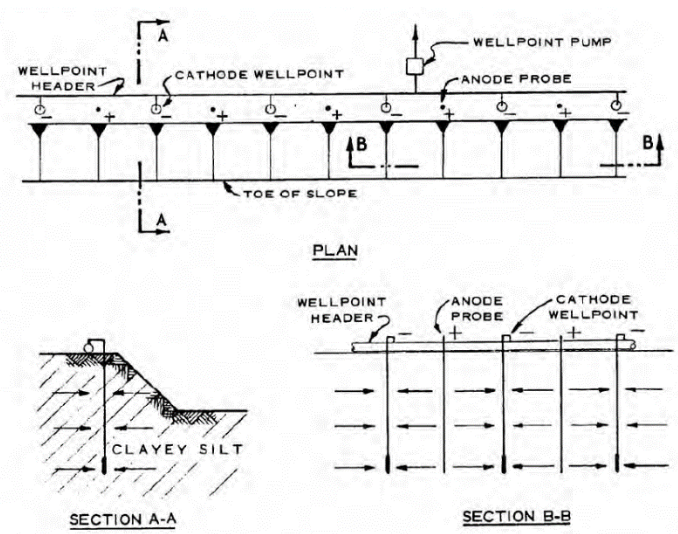


Figure 12 - An Electro-Osmosis Installation [5]

Barrier Walls and Bottom Seals

In certain circumstances, barrier walls around an excavation can be used to reduce the demands on a dewatering system. Barrier walls can reduce the seepage into the excavation and simplify dewatering. They are most effective when there is a very low permeability stratum below a more pervious stratum. The barrier wall can be extended into the very low permeability stratum, cutting off all or most of the seepage into the excavation. Collection and removal of underground water will still be required to remove water stored in the more pervious strata and to remove seepage or leakage through or beneath the wall. Possible technologies for barrier walls include:

- Sheet piles
- Continuous walls constructed with slurry support methods
- Concrete panel or secant pile walls
- Soil mix walls
- Grouting
- Ground freezing

Discussion of barrier wall technologies is beyond the scope of this article but has been discussed in two other publications by one of the authors and his colleagues [5] [6].

In some cases, bottom seals can be used together with barrier walls. The bottom seal resists uplift pressures and prevents upward seepage into the bottom of the excavation. A bottom seal installation is shown in Figure 13. Bottom seals are not practical for large open excavations, but they can be effectively used for smaller excavations for structures such as stilling basins or pump/valve houses.

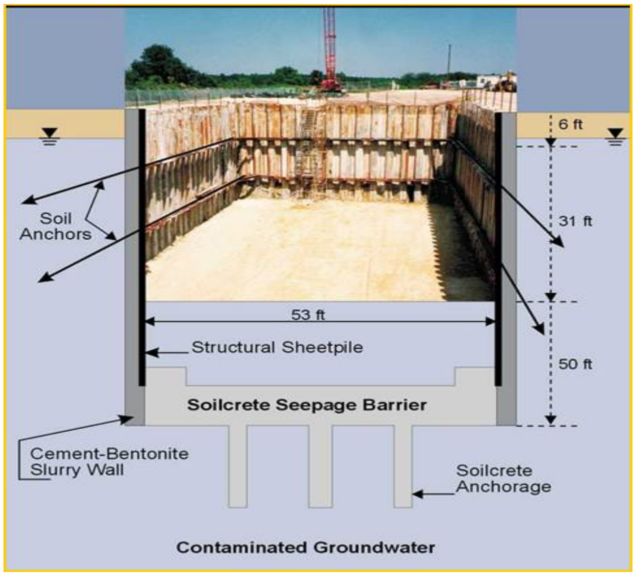


Figure 13 - A Jet Grout Bottom Seal Combined with a Barrier Wall (Courtesy of Hayward-Baker Inc.)

Considerations

Design of dewatering systems requires:

- Investigations and data collection
- Analysis
- Selection of dewatering system and equipment
- Evaluation of power requirements
- Specification of dewatering requirements

Subsurface investigations. Investigations and data collection should be sufficiently comprehensive to understand the geology of the area around and beneath the excavation. Of specific interest is an understanding of the extents, thicknesses, stratification, and permeabilities of the various soil and rock strata. Conventional subsurface investigation techniques, such as borings and penetrometer soundings, piezometers and observation wells, laboratory tests, and geophysical investigations will provide much of the needed information. In addition, in-situ borehole permeability tests can be helpful in identifying hydraulic properties of subsurface strata. However, caution should be exercised in placing too much reliance on borehole permeability test results. In critical dewatering situations, field pumping tests on wells with an adequate number of monitoring piezometers should be considered. These tests, if properly conducted, provide the best indication of how a production dewatering system will perform. Powers et al. [3], includes an excellent chapter on all aspects of pumping tests.

Specialized experience. the advice of individuals with practical dewatering experience can be invaluable in deciding whether pump testing is appropriate.

Design groundwater elevations and chemical quality. Groundwater tables and piezometric conditions need to be carefully evaluated, including consideration of seasonal or operational variations of groundwater conditions. The chemical and biological characteristics of the groundwater also need to be understood, as these characteristics could result in corrosion or fouling of well or wellpoint screens, sand filters, pumps, and piping.

Recharge. It is also important to understand the likely sources of recharge to the dewatering system and their probable fluctuations during the dewatering period. The design and configuration of the dewatering system may be significantly different if the water to be intercepted is primarily from the downstream channel, rather than from the reservoir, which can be the case if the seepage barrier within the dam and its foundation is very effective. In some cases, dewatering flow requirements can be reduced by using pipes to discharge reservoir diversion flows farther down-stream, hence, drying up the stream near the dam and reducing recharge to the dewatering system.

Analysis of flow and drawdown. Analysis of dewatering systems can be completed using numerical analyses, flow nets, or simplified equations and charts. The degree of sophistication of the analyses can be tailored to match the complexity of the geology and the criticality of the dewatering system. If a pumping test performed on a confined aquifer with measurements of piezometric levels, the resulting data can be used in the calibration of a numerical model. A report should be prepared to document the test data as well as engineering analyses of the test data. With the wide usage of personal computers and computer programs, the engineer's first thought is often to use a numerical analysis program for design of a dewatering system. While this may be appropriate in some cases, there are many situations where simplified equations and charts provide an equal or superior solution, along with a more fundamental understanding of how the dewatering system will work. Designers should match the analytical method and as closely as possible to the actual subsurface and recharge conditions. Again, the advice of individuals with practical dewatering experience can be invaluable in selecting the appropriate analytical methods.

Detailed design. Based on the data and analysis, the components of the dewatering system (e.g., types of wells, numbers and depths of wells, well spacing, etc.) are selected and configured. In designing the system, redundancy should be considered in terms of the types and numbers of backup and reserve components to be available on site. Selecting the type of dewatering system depends on the average collection capacity of the dewatering device selected for the deepest excavation that will be made, considering the positions of less permeable interfaces and the hydraulic interference between all of the dewatering devices in the system. Laterally extensive impermeable strata close to the excavation bottom can be used in conjunction with a cofferdam constructed with interlocking sheet piles (or other types of water barriers and support systems) to minimize seepage into the excavation and temporarily retain the soils while the new construction is completed. If there is adequate submergence for deep wells, this type of system can be used with or without sheet pile coffer-dams. If required excavations are narrow with respect to the depth of the pervious formation, partially penetrating wells or wellpoints can sometimes be used to achieve adequate drawdown, while at the same time minimizing the total flow required for drawdown within a shored excavation. Trench boxes often enable the safe construction of sumps in situations where interface seepage is a problem at the required subgrade elevations.

Power supply. An important aspect of the system is power. The selection and specification of the power supply for the dewatering system should be based on availability and reliability of power sources and other considerations, such as possible noise limitations. Typical sources of power are engine power, line electrical power, and generator power. Engine and generator power can be noisy and may not be acceptable in some settings. For critical dewatering systems, on-site, automatically switched backup power should be provided, so that the risk of a dewatering system outage is reduced.

Monitoring. For highly critical systems, it may also be appropriate to require on-site, full time, human monitoring of the system.

Specifications. After system components and requirements are identified, specifications need to be prepared for either a contractor-designed or engineer/owner-designed dewatering system. The specifications need to include all pertinent performance and installation requirements. Typical performance specifications require lowering the phreatic surface in sand strata (or piezometric head in confined aquifers underlying the deepest excavation) to 2 feet below the bottom of the deepest excavation. When the excavation subgrade is in silt, the usual drawdown requirement is 5 feet below subgrade when there will be primarily foot traffic and light equipment operating at subgrade during construction. Where there will be repeated passage of heavy equipment at subgrade elevation in silt subgrades, the required drawdown level will need to be 10 feet or more, and it may also be necessary to improve the subgrade strength to provide adequate trafficability.

Workmanship. It is of utmost importance that the dewatering system be designed and installed such that no solids will be pumped, and the specification should require the contractor to prove that their wells, sumps, wellpoints, and/or other dewatering devices do not pump more than a minimal quantity of solids. A typical specification requirement is a maximum of 5 parts per million (by volume) solids in the pumped water.

Testing. Full-scale system tests with solids content, flow, and drawdown measurements and analysis of such tests, to evaluate the quality (workmanship) and effectiveness of the system in achieving the specified performance criteria are always advisable.

Reporting. Provisions should be made in project specifications and in budgeting for engineering during construction. An engineering memorandum report should be prepared to document the test data as well as the engineering analyses of the test data.

Reservoir drawdown planning and timing. Drawing the reservoir down earlier can reduce dewatering requirements and result in significant cost savings. If the reservoir cannot be drawn down until late in the year, a more robust dewatering system may be required. The timing for reservoir drawdown should be described in the bidding documents. It may be beneficial to develop and include piezometric time series data in the specifications to inform the contractor of the time lag in piezometric head reduction associated with reservoir drawdown.

Contingency for early onset of winter and cold temperatures. Project scheduling and the special conditions clauses need to cover this possibility so that both the Owner and the Contractor fully recognize the effect of earlier-than-expected winter conditions on dewatering. If necessary, the specifications should provide design criteria for winterization of piping systems to allow continued pumping during protracted cold weather.

Provision for dewatering design intervention. Consider including language in the specification that will allow the engineer to intervene in the dewatering design under well defined circumstances; e.g. when performance criteria or workmanship standards are not being met and no progress is being made to correct the problems that exist.

Conclusion

Dewatering requirements for dam construction can be complicated, but they also can be critical to project success. Engaging people with the appropriate experience in selection, design, installation, and operation of the system is essential to successful dewatering.

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[3] Powers, J.P, A.B. Corwin, P.C. Schmall, and W.E. Kaeck, 2007. Construction Dewatering and Groundwater Control – New Methods and Applications, Third Edition, John Wiley & Sons, Inc., New York, NY. See Chapter 9 for planning and performing pumping tests. See Chapter 16 for methods of groundwater control, including open pumping and predrainage methods with a detailed table comparing wellpoint systems and suction wells, deep wells, ejector (jet eductor) systems, and horizontal drains.

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