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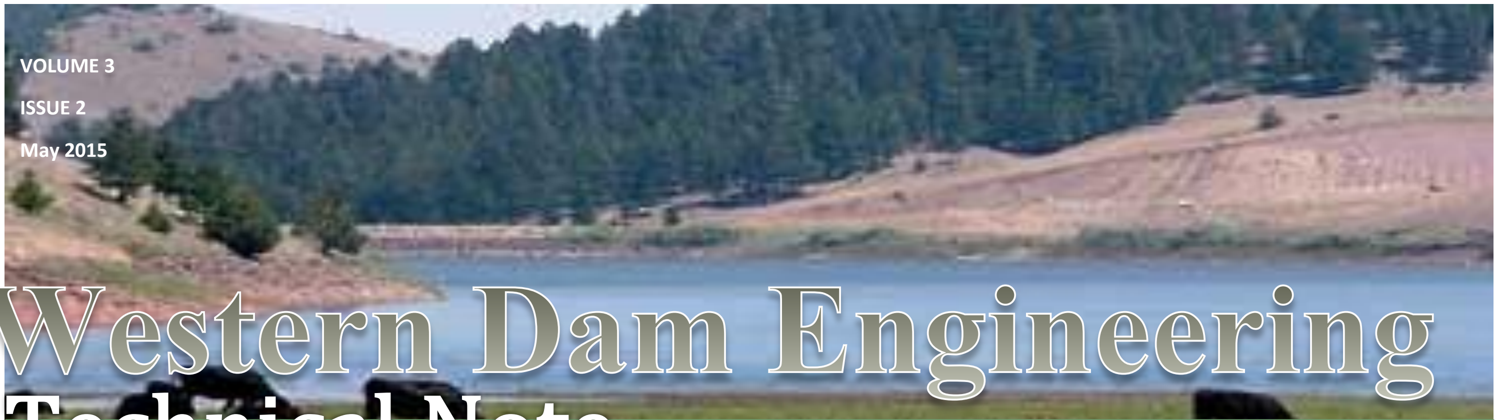

Western Dam Engineering Technical Note

A QUARTERLY PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **spillways on small dams**, **geology 101 for dams**, and a guide to **dam inspections**. Most of these articles draw on previously published articles in this newsletter. 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.

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

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Good to Know

Comments/Feedback/Suggestions?
Email Colorado Dam Safety to submit feedback on Articles. Please use article title as the subject of the email.

Upcoming ASDSO Webinar Dam Safety Training:

- *Waterproofing Systems for Dams, June 9, 2015*
- *Understanding and Managing Plant & Animal Intrusions in Embankment Dams and Levees, July 12, 2015*

Upcoming Classroom Technical Seminars:

- *Conduits, Gates and Valves, June 2-3, 2015, Portland, ME*
- *Soil Mechanics for Earth Dam Design & Analysis, June 23-25, Nashville, TN*
- *Inspection and Assessment of Dams, Aug. 11-13, Pittsburgh, PA*

ASDSO Training Website Link

In this Issue

Dam Safety Inspections…
A Closer Look

Introduction

Safety inspections are an important and necessary responsibility of dam owners. The goal of a safety inspection is to identify potential dam safety deficiencies before they become dam safety incidents. If not corrected, these deficiencies can turn into serious, costly repairs or even dam failures. Dam inspections are also a great opportunity to gather the owners, engineers, experts, regulators and all stakeholders involved with a dam in order to educate, communicate, to delegate responsibilities, to discuss possible failure modes, to plan for emergencies, and to establish long term relationships concerning the dam. This article is intended to be a high level overview of the safety inspection process for small low-hazard dams from planning to implementation. For additional details regarding dam safety inspections, the reader is encouraged to visit the Association of State Dam Safety Officials (ASDSO) website and view the webinar titled, Introduction to Inspecting Dam for Owners and Operators.

Why are Inspections Important?

During an inspection of an emergency spillway, an inspector identified open, unsealed joints between concrete spillway slabs (Photo 1).

Photo 1: Concrete spillway from the inspection report. Photo inset shows an open joint.

The openings were as wide as 1 inch and had vegetation growing in them. A recommendation was made in the inspection report to repair the joints, but the dam owner neglected to implement the repair.

Four years later the spillway operated and the water flowed into the open, unsealed joints causing uplift pressures to develop beneath the slab that ultimately led to the failure of the spillway slabs (Photo 2). It cost the owner more than $1.25 million to reconstruct the spillway. The spillway failure may have been averted if the owner had implemented the repairs recommended in the inspection report. The cost to implement the inspector's recommendation was estimated to be approximately $500.

Photo 2: Failed concrete spillway following operation during a storm event.

Types of Inspections

Typically dam safety organizations and dam owners will conduct a variety of inspections including formal, intermediate, routine, and emergency inspections. Regulatory requirements, hazard classification, dam condition, and special events dictate the scope and frequency of dam inspections. A qualified engineer is required for formal, intermediate, and emergency inspections. Due to safety concerns, some inspection activities may need to be performed as a team or with the aid of specialized equipment. For example, inspections of the conduit may require confined space entry protocols or a remote operated vehicle (ROV). A detailed discussion about conduit inspections was presented in a previous article titled, You Con-du-it; How to Fix a Leaky Pipe.

Who can be an inspector?

People who have:

- Good knowledge of the design, operation, maintenance, and potential failure modes of the dam.
- The physical capability to

traverse rough terrain, steep slopes, remote locations, and long distances.
- Keen observation skills.
- Willingness and motivation to get dirty and wet!
- Good documentation and report writing skills.

Preparing for Your Inspection

The inspection begins long before arriving on site. The well-prepared inspector begins by becoming familiar with site access, design features, construction history, inspection history, and even the type of weather that may be encountered during the inspection.

Assemble Inspection Team – Review the previous inspection reports to see if an additional engineer with structural, geotechnical, or hydraulic experience may be needed to round out the inspection team.

Contact Regulatory Agency – It is worth a quick phone call to the appropriate oversight agency to verify regulatory requirements for inspection (such as a mandatory outlet inspection or concrete condition survey).

Review Recent Weather – Ponded water may not always be a sign of potential seepage. Knowing if the site has recently experienced precipitation events may give the inspector important clues during the inspection.

Review Previous Checklists – Become familiar with what previous inspectors have identified, repairs that have been recommended, and status of completion.

Review Drawings or Construction Documentation – Understanding how the dam was designed or constructed can help identify where potential problems may exist. Note the locations of drainage outlets and instrumentation.

Review Potential Failure Modes – Reviewing the potential failure modes specific to your dam will help focus your efforts on specific components of the dam.

Coordinate with Owner/Operator – Discuss with the owner in advance any activities that can be undertaken to make your inspection more efficient. Can a survey be performed to evaluate differential movement or settlement of structures? Does the stilling basin need to be dewatered? Can the owner operate through the full gate range? Do they need to notify water users of an impending gate closure? What about mandatory minimum releases – will someone get in hot water if you temporarily dewater the stream? Request seepage weirs be cleaned to collect accurate readings. Request that tall grasses and vegetation be removed prior to inspection. It's a lot easier finding a crack or an animal burrow when you're not staring through 3- to 4-foot tall grass (Photo 3)!

Photo 3: The importance of mowing before an inspection.

Review Instrumentation Data – Piezometers and seepage weirs are the first indication that something may have changed. Print out in advance a location map, simple plots, and key information for each piezometer to take with you. Having this information available will help you during the inspection. It's a perfect opportunity to make sure that your survey points haven't walked off with the public.

Assemble Necessary Equipment – It is very important to plan out what equipment you may need for an inspection before you get there, especially if your dam is remote! Equipment may include all or some of the following (Photo 4):

Photo 4: Typical inspection equipment.

- Inspection form (click here for more information), notebook, clipboard, pencil
- Camera, GPS, cell phone, rangefinder

- Hand level & rod, binoculars, probe (old ski pole)
- 100' tape, 25' tape, 6' folding rule, measuring wheel
- Flashlight and/or mirror
- Bucket and timer (to measure seepage rate)
- Stakes, flagging, poke stick
- Aerial photo of inspection area
- Rubber boots, snake chaps, sunscreen, insect repellant, Bear Spray, First Aid Kit, sensible clothing for weather
- Drinking water, food
- Rubber hammer
- Outlet inspection camera and sled, a Do-It-Yourself (DIY) camera and sled was included in a previous article titled, You Con-du-it; How to Fix a Leaky Pipe
- Confined space entry equipment and paperwork
- An experienced yet open and creative mindset

Assemble Documentation – Documentation may include a map or drawings of the dam and the inspection form. Below is a list of some other documentation that may be useful:

- List of potential failure modes
- Previous inspection checklists
- Old construction photos
- Plots of instrumentation data
- List of previous repairs or modifications and repair recommendations
- The dam's electronic project file (if available), loaded on a tablet for reference, if needed
- Talk to last year's inspector about problems or issues and document.

General Inspection Guidance

The purpose of an inspection is to observe every part of a dam and its appurtenant structures to identify changes between inspections. Performing inspections by the same person, during the same time of year under the same type of reservoir loading has advantages and disadvantages. For example, it is important to inspect a dam when the reservoir is at a similar level as the previous inspection to confirm observed seepage is similar to previous inspections. However, there are also advantages to inspecting the dam during different seasons with different people and during different reservoir levels. A late season inspection often provides the inspector the opportunity to see the upstream face of the dam…a good opportunity to look for sinkholes, as described below. If the dam has piezometers, arrangements should be made to measure the static water level during the inspection (preferably at full pool). The inspector(s) may need to have a bit of flexibility in their schedule(s) to see how the dam responds to varying or similar conditions.

Terminology – Make sure to use accurate dam terminology. It's better to use upstream and downstream, left and right – typically facing downstream, instead of using compass directions. Providing clear definitions for good, fair, and poor condition is also important for future inspectors to understand how the condition was assigned.

Use the SIMPLE Rule – For documenting defects, **S**ketch the location of the defect, **M**easure the defect (depth, width, length), **P**hotograph the defect, **L**ocate the defect in reference to a known location (use existing stationing or measure from a known feature like the outlet works or spillway).

Photo Tips – Consistency: Take photos at the same location and orientation as previous photos. Using a scale in the photos helps document size and/or extent of the feature being documented. Photos can be used for comparison if conditions change.

Zigzag vs. Parallel – These are two methods primarily used to inspect a dam: zigzag or parallel (Figure 1). Typically, the zigzag method can be used on small dams by inspectors who are physically fit. The parallel method is useful for steep or rocky slopes. For both methods, it is important to make sure that the inspector stops periodically and turns 360˚ to observe the slopes near and far for anything unusual before continuing on the inspection.

Teamwork – If inspecting with two people, develop a system so that one person is taking photos and keeping the photo log and the other person is measuring and documenting observed conditions. The person with the gym membership can be the one to hike up and down the slopes while the other walks along the crest.

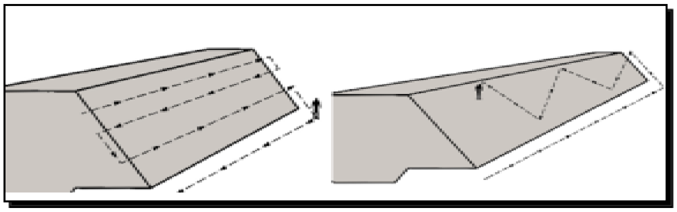

Figure 1: Inspection methods typically follow a zigzag or parallel method.

What Should I Look For?

Safety inspections will cover every visible portion of the upstream and downstream slopes, crest, auxiliary spillway, outlet conduit, outlet structures, and reservoir rim. Although all inspections are comprehensive in nature, the scope of the inspection depends on the type of inspection being performed (e.g., formal vs. intermediate vs. emergency). For inspection tips and guidelines specific to outlet conduits, see the previous article titled, You Con-du-it; How to Fix a Leaky Pipe.

The following sections present some typical deficiencies noted during dam safety inspections and possible causes and consequences.

Upstream and Downstream Slopes

Slide/Slump/Slip (Deep or Shallow):

- Causes: Originated as cracking excessive erosion, over steepened areas, saturation, rapid drawdown
- Consequences: Crest loss and overtopping; shortened seepage path

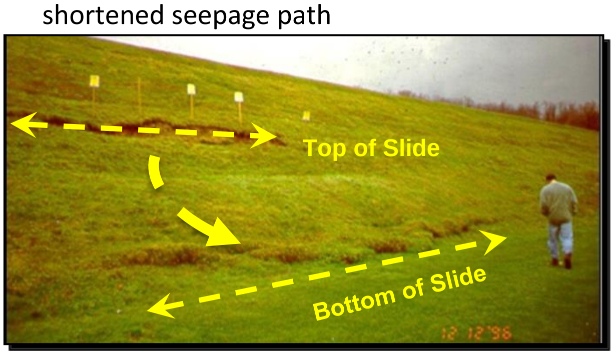

Photo 5: Shallow slide, slump, and slips on a slope (ASDSO)

Photo 6: Deep slide, slump, and slips on a slope (ASDSO)

Sinkhole:

- Causes: Embankment material carried through erosion pipe, collapse of material into animal burrow
- Consequences: May represent a serious piping problem in embankment or foundation

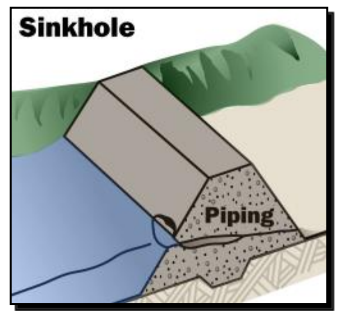

Figure 2: Sinkhole on slopes (AECOM)

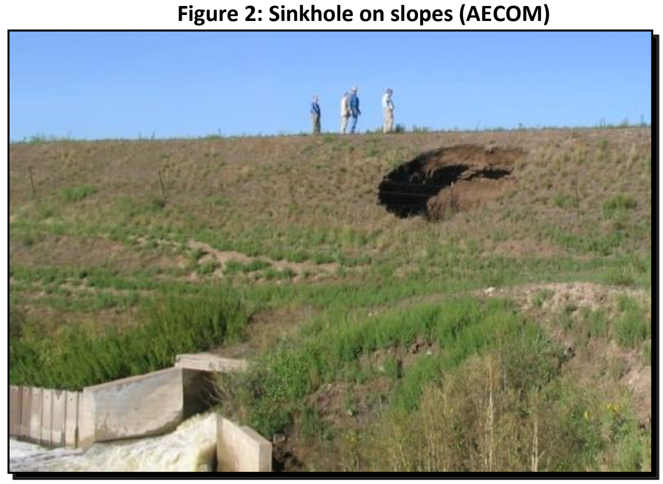

Photo 7: Sinkhole on downstream slope (AECOM)

Broken Down/Missing Riprap and Slope Erosion:

- Causes: Poor quality riprap has degraded, undersized riprap displaced by wave action
- Consequences: Erosion, loss of crest, overtopping

Photo 8: Loss of riprap and slope erosion (Montana DNRC)

Slope Erosion:

- Causes: Rain, snow melt, ponding on crest, poorly maintained crest, vehicles/animal trails, sparse vegetation
- Consequences: Erosion can create gullies, which lead to over steepened area and stability issues

Photo 9: Slope erosion and sparse vegetation (AECOM)

Animal Burrows:

- Causes: Water and vegetation attract wildlife
- Consequences: Preferential seepage paths, erosion, and loss of freeboard

Photo 10: Animal burrow (Montana DNRC)

Crest

Desiccation/Transverse/Longitudinal Cracking:

- Causes: Clay material shrinks as it dries, differential settlement of embankment or foundation, weak embankment material, slide
- Consequences: Shortens preferential seepage path, seepage paths through cracks can lead to internal erosion, slides

Photo 11: Transverse crest crack (ASDSO)

Photo 12: Longitudinal crest crack (Montana DNRC)

Sinkhole:

- Causes: Collapse of embankment material into piping hole or animal burrow, settlement over outlet works conduit
- Consequences: Could represent serious piping problem in the embankment leading to failure

Photo 13: Crest sinkhole (ASDSO)

Low Crest Areas:

- Causes: Settlement, early signs of piping or a void, erosion, poor construction/maintenance
- Consequences: Reduced freeboard can lead to overtopping and failure

Photo 14: Low crest areas (Montana DNRC)

Vegetation:

- Causes: Poor maintenance, excessive water promotes growth
- Consequences: Obscures inspection, tree roots can cause seepage paths, large trees can blow over and their root systems can dislodge soil and reduce freeboard

Photo 15: Crest vegetation (AECOM)

Ruts:

- Causes: Vehicle traffic, poor maintenance, poor drainage
- Consequences: Seepage into embankment from ponded water, loss of freeboard

Photo 16: Crest ruts (ASDSO)

Seepage

Since seepage can occur through the embankment, foundation, abutments, or along embankment penetrations, this topic will be addressed separately.

The most common seepage locations:

- Downstream slope and toe
- Foundation downstream of embankment
- Abutment groins
- Penetrations through embankments

Look for:

- Areas of green, lush/wetland vegetation
- Abrupt changes or horizontal lines of vegetation
- Flowing water
- Turbid, cloudy, or muddy water

Sandboils:

- Causes: Seepage through foundation removes material, high seepage velocities cause sand to “boil”
- Consequences: Continued seepage and erosion can lead to sinkholes and foundation failure and can eventually cause embankment failure

Photo 17: Sandboil (ASDSO)

Cloudy Seepage:

- Causes: Piping or internal erosion, internal crack, pervious zone, or animal burrow; poorly compacted contact between embankment and abutment, seepage occurs in abutments
- Consequences: Progression of piping and erosion of material, failure, abutment slide

Photo 18: Muddy seepage at downstream toe (ASDSO)

Spillways

Open or displaced joints on the spillway walls and slabs can allow uplift pressures to develop as described earlier (Photos 1 and 2).

Obstructions:

- Causes: Vegetation, floating reservoir debris
- Consequences: Reduced spillway capacity can lead to overtopping

Photo 19: Vegetation obstructing spillway flow (AECOM)

Outlet Structures

Concrete Spalling, Honeycomb, Erosion:

- Causes: Erosion from water, poor construction, freeze-thaw action
- Consequences: Rough concrete will erode faster; exposed rebar may cause internal corrosion

Photo 20: Concrete erosion (AECOM)

Damaged Gate or Operator:

- Causes: Broken support block, bent/broken control stem, debris stuck under gate, cracked gate leaf, damaged gate seat or guides, missing limit nut, improper operation (discuss with dam tender)
- Consequences: Inability to close gate reduces water storage, inability to open gate compromises ability to draw down reservoir in an emergency

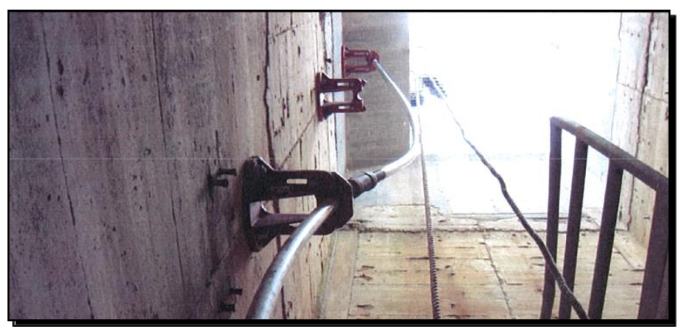

Photo 21: Bent gate stem (AECOM)

Erosion/Undermining:

- Causes: Undersized riprap or loss of riprap, no energy dissipating structure at outlet
- Consequences: Instability of outlet structure, progressive backward erosion into the downstream slope

Photo 22: Erosion and undermining of outlet structure (AECOM)

Reservoir Rim

Landslide Susceptibility:

- Causes: Reservoir water surface increases water level in weak materials in the abutments and surrounding hillsides cause landslides or slope instability
- Consequences: Reduced storage capacity, blocking or damage to intake structure

Inspection Closeout

Before you leave the dam site and begin a long drive back:

- Read through checklist and notes. Are you missing any information? Did you forget to walk an area?
- Are you missing any photos that you thought you took?
- Did you forget to measure seepage or anything else?
- Completely fill out the checklist. Do not be tempted to leave the site before completing this task.
- Kick the dirt or hang out on the pickup hood or tailgate 'office' with the owners for a while longer. The longer you stay the more they will tell you of the real history, maintenance, issues, and problems with a dam and the longer you have to instill some dam safety wisdom. Remember dam safety is about building lasting and trusting relationships with owners and stakeholders. It is not just a short term visit followed by a nasty letter. It is a long term relationship with people.

Now that you are back to civilization, prepare your inspection report:

- Try to write the inspection report as soon as possible before you start to forget details!
- Save photographs and add captions to those that are significant.
- Finalize checklist and prepare a sketch of the dam showing observations/problem areas.
- Compare your observations with previous reports.
- State status of recommendations from previous inspection (e.g., completed, incomplete, deleted), carrying forward incomplete recommendations.
- Make recommendations for maintenance and/or repairs.
- Recommendations should be specific and concise; use accurate terminology, state a time frame for implementation, and have a cost estimate, if applicable.
- Share inspection report with other team members and request their input and review.
- When required, inspections should be submitted to the appropriate regulatory agency following inspection completion.
- Follow up with all stakeholders early and often during the year to discuss issues or to emphasize solutions and strengthen relationships.

Useful References

[1] Association of State Dam Safety Officials. (2013). Introduction to Inspecting Dam For Owners and Operators
[2] United States Department of Homeland Security: Federal Emergency Management Agency. (2004). Federal Guidelines for Dam Safety, FEMA 93.
[3] Association of State Dam Safety Officials. Responsible Dam Ownership: Operation, Maintenance and Inspection.
[4] United States Department of Homeland Security: Federal Emergency Management Agency. (2007). Training Aids for Dam Safety (TADS): A Self Instructional Study Course in Dam Safety Practices, FEMA 609DVD.
[5] United States Department of the Interior: Bureau of Reclamation. (2000). Safety Evaluation of Existing Dams (SEED): A Manual for the Safety Evaluation of Embankment and Concrete Dams.
[6] United States Department of Agriculture: Natural Resources Conservation Service. (2014). Formal Dam Inspection Checklist, WV-ENG-105.

Example Checklists

Montana Example Checklist

Colorado Example Checklist

Wyoming Example Checklist

Association of State Dam Safety Officials

Spillways on Small Dams

Introduction

The purpose of a spillway is to safely convey reservoir inflows over and/or around a dam to the natural drainage channel, up to and including the Inflow Design Flood (IDF), thus protecting the dam embankment from failure due to overtopping. The IDF varies according to jurisdiction and dam hazard classification. In addition to providing sufficient flood capacity, the spillway must be hydraulically and structurally adequate and must be located so that spillway discharges do not erode or undermine the dam. Flow over spillways is a designed event and are usually not a cause for alarm on an appropriately designed and constructed dam and spillway.

Different states in the US categorize spillways differently. For example in Colorado, the State Engineer's Office (SEO) document titled *Rules and Regulations for Dam Safety and Dam Construction* defines an auxiliary spillway, as defined by US Bureau of Reclamation (Reclamation), as an emergency spillway. It is therefore recommended that the reader consult relevant state guidelines/legislation to understand the terminology used in each state. *Design of Small Dams* (Reclamation 1987) categorizes spillways as service, auxiliary, and emergency. These are described below.

Service Spillway: A service spillway is the overflow structure designed to limit or control the operating level of a reservoir, and the first spillway to be activated. Service spillways are designed to pass part of the IDF unless the service spillway is unavailable at the time of flooding due to damage, blockage, or inoperability. Service spillways are designed to pass floods that occur frequently and damage to a spillway from the passage of these floods would not normally be tolerated. Service spillways rarely appear on small water supply dams, but frequently appear on flood control dams.

Auxiliary Spillway: An auxiliary spillway is used in conjunction with a service spillway, if present, to pass the IDF. Auxiliary spillways are designed to operate for floods in excess of the flood flow used for the design of service spillways or, if a service spillway were not present, all inflows that are not stored or released through the outlet works. If used in combination with a service spillway, an auxiliary spillway may not need to be designed for the same degree of safety required for other structures and some flood damage may be considered tolerable for more infrequent flood events. In some cases, this may offer considerable construction cost savings. Spillway damage that would affect the ability of the reservoir to retain water or would threaten the integrity of the dam would not be tolerable. Flood damage to an auxiliary spillway and the associated repair and maintenance costs need to be considered during the design process. Auxiliary spillways are a common form of spillway on small dams and are the main focus of this article.

Emergency Spillway: Emergency spillways are provided for additional safety should emergencies not contemplated by normal design assumptions arise. Such emergencies may include damage to, or issues with, the service and/or auxiliary spillway or damage/malfunction of spillway gates. Under normal reservoir operation, emergency spillways are never required to function and the crest level is set above the maximum reservoir water surface resulting from the IDF. Emergency spillways rarely appear on small dams, particularly small dams with a passive (ungated) auxiliary spillway.

The design of a spillway that is both functional in terms of design, and economical from a construction cost standpoint, requires careful consideration of the associated topography, the geology, the spillway type, maintenance and operational requirements, the IDF, the dam type and the proximity of the dam to the spillway. To select an optimized and economical spillway and dam configuration, construction cost estimates are typically developed for various combinations of spillway capacities, spillway types, and dam heights.

If possible, a spillway should be located independently of the dam itself, on the left or right dam abutment, or in a saddle or depression along the reservoir rim. The locations considered should lead to a natural waterway or a gently sloping abutment where an excavated channel can be constructed beyond the dam to avoid the possibility of damage to the dam or other structures.

A spillway generally consists of various combinations of crest control structure, conveyance element (or chute), terminal structure, and downstream channel. As most small dams are embankment dams, only spillways typically associated with embankment dams are discussed in this article. Therefore, spillways typically associated with concrete dams, such as free overfall drop spillways or overtopping spillways, are not discussed. The following sections provide examples of various crest control, conveyance, and terminal structures for embankment dam spillways.

Crest Control Structures

A major component of a spillway is the crest control structure that regulates outflows from the dam. A crest control structure can be categorized as either a controlled (gated) or uncontrolled (ungated) crest structure. Most crest structures on small dams are uncontrolled for simplicity, economical construction cost, and ease of maintenance and operation. As the focus of the *Western Dam Engineering Technical Note* is predominately on small dams, uncontrolled crest structures are discussed herein.

There are six common types of uncontrolled crest structures and these are described in the following subsections of this article. For a crest control structure to realize its theoretical discharge, the hydraulic conditions both upstream and downstream must be acceptable. The approach conditions upstream should not choke the flow to the crest and the downstream conveyance element should not cause excessive submergence of the crest. In some cases, sub-optimal downstream hydraulic conditions are acceptable to achieve efficiencies in design and construction cost.

Ogee Crests

An ogee crest has a control weir that is curved in profile and is designed to closely profile that of the lower nappe of a ventilated sheet (of water) falling from a sharp crested weir. An ogee crest can also be designed so that negative pressures on the crest are within an acceptable range and the potential for cavitation is minimized. A correctly designed ogee crest control structure has high discharge efficiency and is used on most spillway control crests for large dams and commonly on small dams. An example of an ogee crest control structure is shown on Figure 1 and Figure 2.

Figure 1: Ogee Crest

Figure 2: Ogee Crest

Broad Crested Weir and Concrete Sill Crests

The crest structures on many small dams, especially where space permits and where minimal discharge capacity is required, may be simple concrete sills or broad crested weir control structures. Occasionally, broad crested weirs will have a slightly rounded upstream edge to provide a more efficient inlet flow transition. Where concrete broad crested weirs are not located significantly above the channel bed to develop hydraulic control, these weirs are referred to as 'sills'. Examples of a broad crested weir and a concrete crest sill are shown on Figures 3 and 4, respectively.

Figure 3: Broad Crested Weir


Figure 4: Concrete Control Sill

Sharp Crested Weirs

A sharp crested weir is typically formed through the construction of a thin wall and placed normal to the flow in a spillway chute. The flow depth is generally two or more times greater than the wall thickness. Sharp crested weirs often have air vents on the underside of the flow so that atmospheric pressure exists on the underside of the nappe. Sharp crested weirs are seldom used on spillways for dams and are more common in canals and flood control channels. An example of a sharp crested weir is shown on Figure 5.

Figure 5: Sharp Crested Weir

Labyrinth Weirs

Labyrinth weirs provide additional crest length across the width of a spillway to increase discharge flows, particularly at low heads. The additional crest length is obtained by utilizing a series of trapezoidal walls that provide ’cycles’ on the crest. The walls are typically thin walls that are supported on a concrete slab or other acceptable foundation. Flow patterns on a labyrinth spillway are complex. When the maximum design head for a given labyrinth weir configuration is exceeded, the discharge coefficient can decrease due to interference from adjacent labyrinth cycle(s) which can partially, or fully, submerge the weir crest. At high design heads the labyrinth discharge can begin to approach that of a broad crested weir. As with all crest structures, a labyrinth weir is sensitive to tailwater levels and when the crest becomes submerged the discharge coefficient can decrease significantly. A piano key weir offers similar discharge efficiency to a labyrinth weir, and in some cases greater discharge efficiency than a labyrinth weir. Piano key weirs are rarely constructed on small embankment dams and, therefore, are not discussed herein. An example of a labyrinth weir control structure is shown on Figure 6.

Fusegates® are most often designed with a labyrinth crest shape for more efficient discharge and to minimize the number of Fusegates® required to pass the IDF. Fusegates® are a more common installation on large dams and, therefore, are discussed no further in this article.


Figure 6: Labyrinth Weir

Drop Inlet/Morning Glory Crests

A drop inlet crest is one in which the flow enters the spillway over a horizontal lip, drops through a vertical or sloping shaft, and then flows through a horizontal or near horizontal conduit or tunnel to the downstream river channel. Drop inlets are commonly used for principal spillways and less frequently for auxiliary spillways. The drop inlet is normally located within the reservoir so flow can enter from the entire perimeter or from one or multiple sides of the crest. The profile of a drop inlet crest can be square or round, and in some cases, can have an ogee crest-shaped lip to efficiently discharge flows. On large spillways, it is common to construct guide vanes or piers at the crest to prevent the formation of flow vortices which can lead to sub-optimal hydraulic conditions and reduce discharge. Discharge control can shift from crest to the throat, or to the conveyance tunnel for these types of spillways. Where the inlet is funnel-shaped, it is often called a "morning glory" type crest structure. Morning glory crest structures (Figure 7) are more prevalent on large dams. A more common drop inlet for smaller dams is shown on Figure 8.

Figure 7: Morning Glory

Figure 8: Drop Inlet

Side Channel Crests

Typically a side channel spillway has a control crest located parallel to, and along one side, of the spillway chute. In this case, flow enters from the crest and then turns 90-degrees into the spillway chute. In some cases, a control crest is also located at the upstream end of the spillway chute to provide additional discharge. The side channel spillway crest can be configured with most of the above-mentioned crest types. Due to its unique shape with a long crest and narrow chute, a side channel spillway can often be well-suited to a narrow and/or steep dam abutment. Where suitable, a bathtub crest structure can also be considered if a crest is located on both sides and the upstream end of the chute. Weir capacity and channel capacity must be balanced in the design of these spillways to consider the submergence effects on the weir crest. An example of a side channel spillway is shown on Figure 9. A bathtub crest structure is shown on Figure 10.

Figure 9: Side Channel Spillway

Figure 10: Bathtub Crest Structure (Reclamation 1987)

Conveyance Systems

Conveyance systems are typically chutes or channels that convey flow from the spillway crest structure to the terminal structure. Conduits and tunnels are also used for conveyance systems but are less common. Chute conveyance systems are described in the following subsections of this article.

Spillway Chutes or Channels

An open channel that conveys flows directly from the crest into a stilling basin or downstream channel is referred to as a chute conveyance system. Spillway chutes are commonly located along one of the dam abutments or through a saddle some distance from the dam. A spillway chute is the most common conveyance system, particularly on small dams.

Spillway chutes typically have a prismatic cross section. The most common concrete chute design is a rectangular channel; however, trapezoidal channels are also common. Chutes can be converging or diverging from the crest structure to the terminal structure. Chutes can be lined with concrete, riprap, Reno mattresses, articulated concrete blocks, etc., or be unlined where acceptable foundation conditions exist to resist unwanted erosion during operation. In some instances, a chute can be partially unlined and lined where only certain areas of the foundation need to be protected.

The spillway chute can be smooth, rough, stepped, or baffled. Stepped and baffled chutes can help dissipate the energy of flood flows and can reduce the size of the terminal structure or in certain circumstances negate the need for a terminal structure. Spillway chutes can be designed with a constant slope or with vertical curves and variable slopes to match the dam configuration, site constraints, and/or topography. Typically, and preferably, spillway chutes are straight, but in some cases, have horizontal bends where complex flow conditions can occur and must be considered as part of the design process.

Examples of a lined spillway chute are shown on Figures 11 and 12. An example of an unlined spillway chute is shown on Figure 13.

Figure 11: Lined Spillway Chute (Concrete)

Figure 12: Lined Spillway Chute (Articulated Concrete Blocks and Riprap)

Figure 13: Unlined Spillway Chute

Conduits or Tunnel Outlets

Conduits and tunnels are used to convey spillway flows around or through a dam. These types of conveyance structures are typically used with a drop inlet spillway crest, although some overflow crests and side channel crests discharge into conduits.

Conduits typically have a vertical or near vertical shaft section directly below the inlet and then a nearly horizontal section of conduit or tunnel through or around the dam to the outlet. Most conduits or tunnels are designed to flow partially full, although many drop inlets have a shorter section of the conduit that will remain pressurized at the control point. Proper aeration is critical for conduits to operate smoothly and avoid cavitation, burping, and surging.

Conduit or tunnel linings are typically cast-in-place concrete. Some conduits consist of steel pipe that may have a cast-in-place concrete encasement to resist external pressure.

Terminal Structures

Terminal structures are required where energy from the spillway flow must be dissipated before being discharged to the downstream channel. In some cases, such as where the downstream channel is not erodible, a terminal structure may not be necessary. The more common types of terminal structures provided at small dams are described in the following subsections of this article.

Hydraulic Jump Stilling Basins

The most common type of stilling basin is the hydraulic jump stilling basin. A hydraulic jump stilling basin is used to dissipate kinetic energy by the formation of a hydraulic jump at the interface between a lined spillway and the downstream channel. The stilling basins are typically lined with concrete to avoid scour and erosion. *Design of Small Dams* (Reclamation 1987) documents typical jump style stilling basins for different ranges of Froude numbers (F_r). Froude numbers are related to the kinetic flow factor of the discharge entering the basin. Typical Reclamation stilling basins are summarized in Table 1, which also references Figures 14 through 17. It should be noted that stilling basins often have minimum tailwater requirements for correct operation.

Table 1: Typical Reclamation Stilling Basins

Basin Type	Description	Applicable Range of Froude Numbers
Basin I (Figure 14)	Hydraulic jumps on horizontal aprons	$1.7 < F_r < 2.5$
*Basin II (Figure 15)	Stilling basins for high dams and earth dam spillways	$F_r > 4.5$
**Basin III (Figure 16)	Short stilling basins for small spillways	$F_r > 4.5$
Basin IV (Figure 17)	Transitional jump stilling basins	$2.5 < F_r < 4.5$

* Not often applicable for small dams; ** Incoming velocities not to exceed 50-60 fps

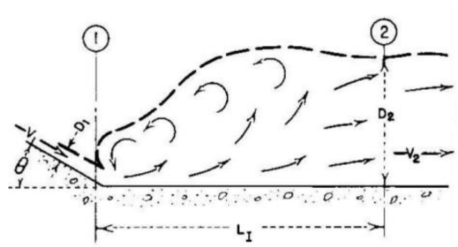

Figure 14: Type I Hydraulic Jump on Horizontal Apron

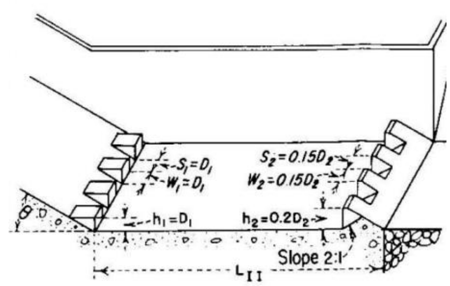

Figure 15: Type II Stilling Basin

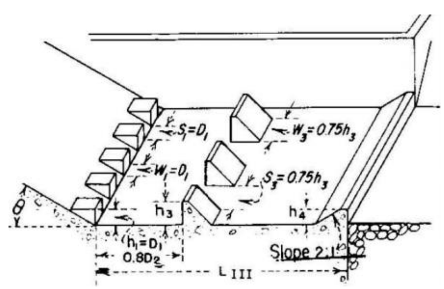

Figure 16: Type III Stilling Basin

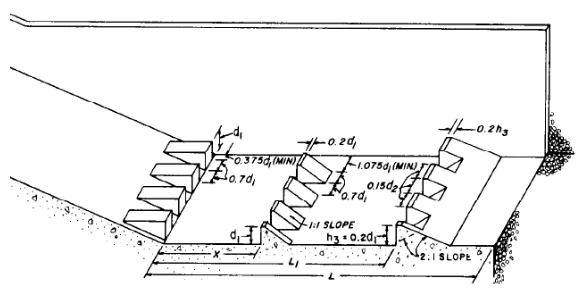

Figure 17: Type IV Stilling Basin

Roller Buckets and Flip Buckets

Roller bucket and flip bucket terminal structures are not described herein, as they are typically provided with large dams/spillways and concrete dams.

Impact Basins

An impact style stilling basin does not depend on tailwater and can be used on either a conduit or open channel conveyance system. Energy dissipation is accomplished by discharging the high velocity jet into a vertically hanging baffle. Care must be taken not to submerge the outlet conduit with tailwater and inhibit downstream venting unless alternate means for venting the outlet conduit are provided. Typically, the area downstream of the baffle is protected with riprap. An impact basin is typically located so that the tailwater is approximately half way up the baffle. An example of an impact basin at the end of a conduit is shown as Figure 18. An impact basin can also be fitted to a rectangular chute.

Figure 18: Impact Basin

Plunge Pools

A plunge pool is the terminal structure defined by the location where a free overflow spillway or a flip bucket discharges into the downstream channel. Plunge pools can consist of either naturally forming scour holes in the channel, or can be artificially created by construction of a downstream sill or excavation into the streambed. Plunge pools can either be lined or unlined, depending on streambed materials and erodibility of the material with respect to the energy that must be dissipated. Lining usually consists of either concrete or riprap. The volume and depth of the hole are related to the range of discharges, the height of the drop, and the depth of available tailwater.

Downstream Channels

The stability of the downstream channel must be understood to guard against headcutting or sidecutting at the toe of the spillway and the potential to threaten the integrity of the spillway, river channel, or the dam itself.

The downstream channel can be described as natural or modified, and can be categorized as unlined rock or soil, armored, or vegetated or a combination of these.

The downstream channel type, natural river geomorphology, and the behavior of the tailwater must be considered with regard to the tailwater requirements for the terminal structure.

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Geology 101 – Dam Good Foundations

Introduction

The behavior and performance of manmade structures (buildings, dams, roads, tunnels, etc.) depend on the foundation that supports them. A foundation is formed by existing geology at the site. Being familiar with geology and being able to identify the foundation's rock or soil type assists in developing an understanding of what types of issues should be considered when designing, constructing, modifying, or repairing a structure.

Understanding how to deal with issues related to geology can prevent costly mistakes. (What makes the situation better, what makes it worse?) What are the limitations of different soil and rock types?

Figure 1 - Leaning Tower of Pisa

Recognizing basic geologic conditions can help evaluate how dams will behave with respect to seepage, settlement, slope stability, piping, and other problems that affect dams.

Civil engineers like Terzaghi, Peck, and Leggett, recognized that major engineered structures were constrained by the foundations they were placed upon or the materials available for their construction. It could be argued that these men coined the term "Engineering Geologist", which is a way to differentiate the study of geology as it is applied to the use of earth's natural materials to house (tunnels, pipelines, underground structures), found (structures with shallow to deep foundations), and build (dams, dikes, levees, concrete) engineered structures.

This article is intended as a geologic primer for the basics of geology and geologic principles, different rock and soil types and simple ways to distinguish between them, and potential issues affecting dams as related to different types of geology.

Rock

The three classes of rock are igneous, sedimentary, and metamorphic. Igneous rocks are formed by cooling and crystallization of liquid rock materials and as a result have distinctive texture and composition. Sedimentary rocks form at the earth's surface through the activity of the hydrologic system. Two main types of sedimentary rocks are clastic rocks, consisting of rock and mineral fragments, and chemical or organic rocks consisting of chemical precipitates or organic material. The conglomerate shown in Figure 2 is an example of a clastic sedimentary rock.

Figure 2 - Outcrop of Conglomerate

Metamorphic rocks result from changes in temperature and pressure and the chemistry of pore fluids. Igneous and sedimentary rock can each be subjected to these forces to become metamorphosed.

Minerals are formed by compounds of elements. The most common compounds are silicates, carbonates, oxides, and sulfates. These compounds form hundreds of minerals, but there are a few common rock-forming minerals that can be easily identified in the field to help classify rocks. Silica and feldspar are the most abundant minerals in the upper part of the earth's crust. Using a quartz, alkali, plagioclase (QAP) diagram, the percent of quartz, plagioclase feldspar, and alkali feldspar is estimated and gives the rock type. Figure 3 shows a QAP diagram for intrusive igneous rocks and Figure 4 shows a QAP diagram for extrusive rock.

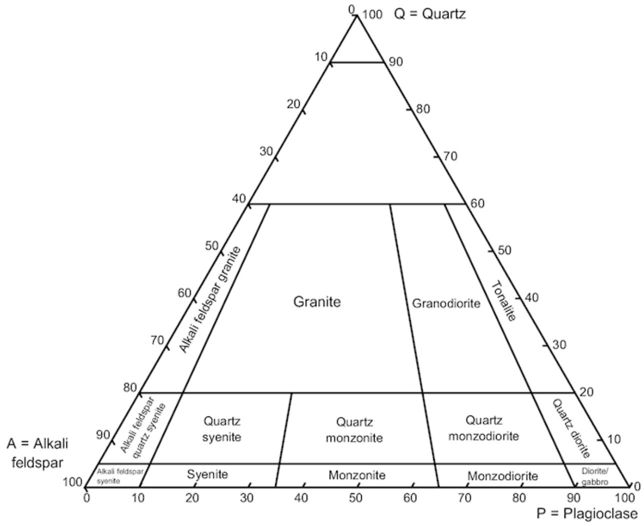

Figure 3 - QAP Diagram for Intrusive Rock

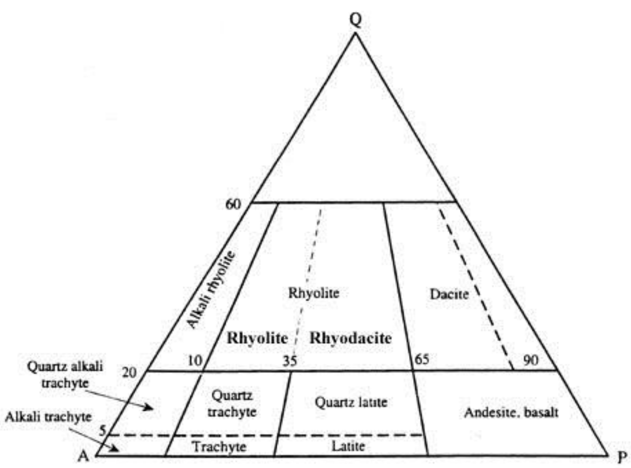

Figure 4 - QAP Diagram for Extrusive Rock

Igneous rocks are an assemblage of crystalline minerals. Igneous rocks started as molten masses of minerals and elements. As these masses moved away from their sources and cooled, the minerals in the mix cooled and solidified into rock. Igneous rocks are classified by whether they cooled below or above the earth's surface and by the texture and type of minerals. Igneous intrusive rocks form below the earth's surface. Igneous extrusive rocks formed as the molten magma cooled at or above the ground surface. Texture of igneous rocks can be fine-grained (aphanitic) or coarse-grained (phaneritic) depending on how quickly the magma cooled. Intrusive rocks, such as granite, diorite, and gabbro, cooled slowly at depth, are medium- to coarse-grained and usually dark colored. Figure 5 shows an example of a coarse-grained granite and a fine-grained basalt.

Sample of Granite   Sample of Basalt

Figure 5 - Examples of Igneous Rocks

A pegmatite is a granitic rock that cooled slowly and allowed feldspar, quartz, and mica crystals to grow large. Although these rocks are beautiful, from an engineering standpoint, they present more problems than rocks with smaller and tighter crystal structures. Figure 6 shows an example of granitic igneous intrusive rock at Half Dome in Yosemite Valley.

Figure 6 - Igneous Rock at Half Dome in Yosemite

Extrusive rocks such as basalt and andesite lava flows cooled fast at the surface, are fine-grained, and are usually dark colored like the basalt flow shown on Figure 7.

Figure 7 - Basalt Flow in Hawaii

Clastic sedimentary rocks, such as conglomerate, sandstone, and shale are formed from the fragments of other rocks. Limestone is an example of an organic sedimentary rock.

Most people who drive on I-70 near Denver will be familiar with the road cut shown on Figure 8. This cut slope exposes an example of a sequence of sedimentary rock that has been tilted from uplift of the Rocky Mountains.

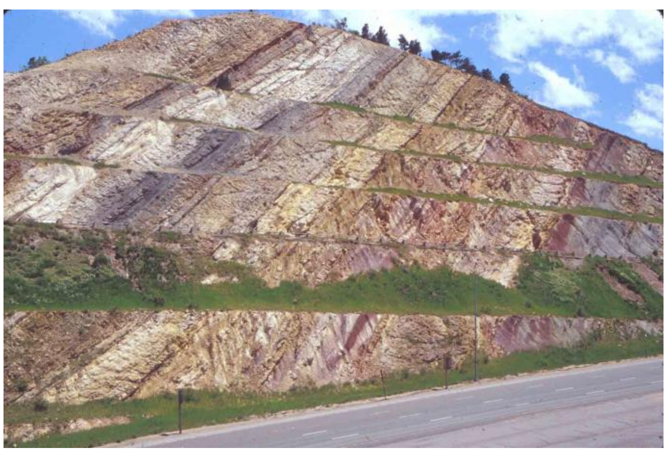

Figure 8 - I-70 Road Cut in Sedimentary Rock just West of Denver

Not all sedimentary rocks are created equal and there are categories of strong rock and weak rock. Throughout the west, many sedimentary rocks were deposited during a time when an inland seaway dominated the area. The rocks deposited in this environment are fine-grained sandstones, limestones, shale, and mudstones. A few examples of these rock types are shown on Figure 9 and Figure 10, respectively.

Sample of Sandstone   Outcrop of Limestone

Figure 9 - Examples of Sandstone and Limestone

Thin layers of Shale   Blocky Mudstone

Figure 10 - Examples of Shale and Mudstone

Sedimentary rocks are layered or stratified. The layers, or stratigraphy, are called beds and represent changes in the energy in the depositional environment, sediment particle size, sediment composition, or time between deposition of individual beds. Bedding is the most dominant structural feature in sedimentary rock and often has the most significant impact on the engineering properties of the rock. Bedding planes are often the weakest part of sedimentary rocks since they are breaks in the overall rock mass. The degree of consolidation and cementing of particles impact the nature of sedimentary rocks. Older rocks, buried deeply and subjected to great pressures, will be stronger and more resistant than younger rocks not subjected to those forces.

Metamorphic rocks are an assemblage of crystalline minerals, formed when an existing rock, which can be sedimentary, igneous, or even metamorphic, is changed due to heat and pressure. Metamorphic rocks that partially melt often retain minerals and characteristics of the parent rock. During metamorphism, new crystals grow in the orientation of least stress, producing a planar element in the rock called foliation. The three main types of foliation are (a) slately cleavage, (b) schistosity, and (c) gneissic layering or banding as shown on Figure 11. Rocks with only one mineral such as limestone or sandstone do not develop strong foliation but instead develop a granular texture with larger crystals.

Figure 11 - Outcrop of Metamorphic Gneiss (Pronounced "Nice")

Gneiss is identified by its alternating light and dark layers and usually wavy appearance. Quartzite usually resembles sandstone but the sand grains are fused together. Figure 12 shows an example of gneiss and quartzite.

Sample of Gneiss Sample of Quartzite

Figure 12 - Examples of Metamorphic Rocks

Weathering

Weathering is a process that decomposes all geologic materials into a soil over time. Weathering can be a physical process or a chemical process. Physical weathering occurs when wind, water, waves, ice, and other environmental conditions break down a rock and transform it into soil. This break-down process can occur in-place or it can result in erosion of the rock into particles that are transported and deposited as a soil at some other location. Generally, the properties of soils formed by in-place physical weathering retain some of the characteristics of the parent material.

Chemical weathering occurs when chemical reactions between minerals and other compounds cause disintegration of rock. Exothermic chemical reactions result in an increase in volume that tends to break rocks apart. The most common chemical reactions are hydration, hydrolysis, solutioning and oxidation.

The type of material resulting from chemical weathering is based on the chemical composition of the parent rock and the type of reaction. For example, hydrolysis is the reaction of a mineral with water to produce a new mineral. An example of this is when feldspar reacts with water to form kaolinite – rich clay soil.

The weathering process is very complex and entire books have been devoted to characterizing the properties of weathered rocks and how they behave. Weathered rocks have a wide range of properties and are probably the most difficult material to characterize. As a result, they have been the focus of many financial claims during construction projects. The effects of weathering degrade all rocks that are exposed to these physical and chemical weathering processes, so it is highly likely that most excavations will encounter weathered rock. When dealing with weathered rock, it is important to recognize that engineering properties may change over very short distances and depths. Table 1 presents descriptions for weathered rock and some basic field recognition tests.

Table 1 - Weathering Descriptions and Field Identification

Weathering Description	Field Recognition
Fresh	No discoloration; hammer rings when rock is hit
Slightly Weathered	Surface discoloration only; rock strength unaltered
Moderately Weathered	Discoloration penetrates rock slightly; iron minerals have rusty appearance; rock is slightly weakened
Highly Weathered	Discoloration penetrates throughout rock; iron minerals altered to clay; rock is weak and can be broken by hand or with light hammer blows
Decomposed	Completely discolored, feldspar and iron altered to clay; quartz may be unaltered;, partial rock structure may remain, but mostly resembles soil

Soil

Most soils form from physical processes as material is eroded from one location, transported by wind, water or gravity, and then deposited in a new location. These soil deposits are named based on their depositional environment. Some examples of these materials include alluvium, colluvium, eolian, and glacial drift. There are other depositional environments that have unique types of deposits such as material deposited by landslides or other mass wasting events. Soils formed by deposition will consist of unconsolidated particles of clay, silt, sand, gravel, or boulders depending on the parent material and the depositional environment (i.e., high energy river deposits that have gravels and boulders or low energy marine deposits that have clays and silts).

Alluvium describes materials deposited by moving water. These deposits are stratified layers of clay, silt, sand, gravel, cobble and boulders depending on the energy of the flow. If the flow of water is very fast, the material that is deposited is coarse-grained (gravel, cobble and boulder). If the flow of water is very slow the material deposited is fine-grained (clay and silt).

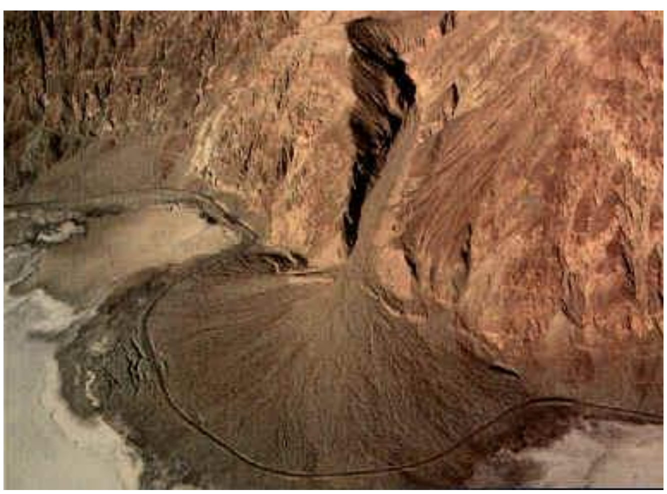

Figure 13 - Typical Alluvial Fan Deposit. Rock is Eroded from Above and Deposited Below as Soil.

Figure 13 shows an example of an alluviual fan deposit at the mouth of a canyon. In this example, coarse-grained material is deposited near the mouth, where the flow of water is fast and fine-grained material is deposited near the perimeter of the fan, where the flow of water slows and loses energy. Alluvial deposits are heterogeneous and can have interbedded layers of clay and silt within thick beds of gravel and cobble. Due to the action of water and movement of the particles, alluvial deposits are characterized by an assemblage of sub-rounded to rounded particles. Some typical engineering properties of alluvium are listed below:

<u>Coarse-grained alluvium</u>

- Highly permeable
- Good source of aggregate
- Good bearing capacity in gravel and cobble
- Low shrink and swell potential
- Sand deposits can be liquefiable

<u>Fine-grained alluvium</u>

- Low permeability
- Low bearing capacity
- High shrink and swell potential
- Low shear strength

Colluvium describes material deposited by gravity. Weathered rock and soil can creep slowly downslope by gravity or material can be deposited relatively quickly as blocks of rock and other lithic fragments fall to the bases of slopes and are incorporated into a matrix of material. The matrix of material at the base of a slope can be coarse-grained or fine-grained. Coarse-grained deposits are sometimes called tallus. Colluvium is a heterogeneous deposit that usually consists of a random mixture of large fragments of rock in a fine-grained matrix that can be composed of material ranging from sand to clay. Since colluvial deposits have been transported relatively short distances, the larger particles, or clasts, are characteristically angular to sub-angular. A few typical engineering properties of colluvium are listed below.

- Extremely heterogeneous
- Usually contains large rock fragments
- Usually at natural angle of repose; cut slopes can be unstable
- Can have tendency to move
- Coarse deposits are usually difficult to excavate

Eolian soils are deposited by wind. These soils are usually composed of sand and silt sized particles. The coarser sand sized particles can form dunes such as the dunes found in the Mojave Desert in California. The fine-grained silt (loess) stays suspended in the air longer than the sand, and as a result, loess deposits usually accumulate down-wind of dunes and other arid desert environments. Some engineering properties of eolian soils are listed below:

- Prone to hydro-collapse
- Can be liquefiable
- Poor resistance to erosion
- Sand deposits can be a source for fine aggregate
- Low expansive
- Easy to excavate

Glacial drift is a general term that describes material deposited by glaciers. There are many terms used to describe the particular deposits from glaciers, but the two main modes of deposition are either directly from the glacial ice (these deposits are called till), or from streams of melt water (these deposits are called outwash).

Generally, glacial till is deposited when the glacier retreats and dumps sediment as ice melts. This sediment, sometime called moraine, is defined by where it was deposited. For example, terminal moraine is deposited at the furthest downstream front of the glacier as it begins to retreat; lateral moraine describes the material deposited on the sides of the glacier as it retreats. Glacial till is extremely heterogeneous, non-stratified, poorly sorted, and contains particles of all sizes that are angular to sub-rounded.

Glacial outwash deposits are similar to alluvial deposits and consist of stratified gravel and sand layers. Due to transport by flowing water, these deposits have well-sorted and rounded to sub-rounded particles.

Some engineering properties of glacial drift are listed below.

Glacial Till

- Permeable to highly permeable
- Extremely heterogeneous mix
- Good source of aggregate
- Difficult to excavate
- Good bearing capacity

Glacial outwash

- Highly permeable
- Can be liquefiable
- Good source of fine aggregate
- Good bearing capacity
- Low shrink and swell potential

Dam Issues Related to Geology

Rock Foundations

In most cases, foundations composed of igneous or metamorphic rocks are well-suited for construction of embankment dams. Igneous and metamorphic rocks are generally much stronger than the soil materials used to construct embankment dams. The stability of foundations and abutments for igneous or metamorphic foundations are mostly a function of the degree of jointing and weathering. Geologic investigations for rock dam sites focus the potential effects of those features on the structures.

Perhaps the most significant problem associated with embankment dams with foundations composed of igneous or metamorphic rocks is related to seepage. Seepage could simply be a water loss problem and not necessarily a dam safety issue when the reservoir basin and abutments cannot hold water. Additionally, when an earthen embankment is constructed on top of a fractured bedrock foundation, care must be taken to prevent internal erosion and piping. When fractures and joints in the foundation are wide enough and continuous, seepage passing through the embankment becomes concentrated into these rock defects. This concentrated seepage induces high seepage velocities/forces that can lead to mobilization (internal erosion) of the overlying embankment material into the foundation. This condition was not well recognized by early dam engineers and has become a prominent failure mode during risk assessments of older dams.

Problematic types of sedimentary rock for dam foundations include shales, mudstones, and other fine-grained rocks. One of the reasons fine-grained sedimentary rocks are problematic is the relatively low strength material that composes them. Geologically young, clay-rich fine-grained sedimentary rock found in much of the west has the tendency to slake. Slaking occurs in fine-grained sedimentary rocks when they are exposed to air. Slaking essentially causes a rock to deteriorate and breakdown. Some types of shale and mudstones begin to slake immediately after they are exposed to air. With shale, the process of slaking usually results in cracking along thin shale layers causing the layers to open like pages in a book. With mudstones, slaking usually results in cracks forming throughout the mass of rock eventually causing the rock to break up into small cubes.

Not all shale deposits and mudstones behave this way. Investigations must be performed on these materials to test how they will behave and perform as a dam foundation. Depending on the chemical composition and minerals that form the rock, the effects of slaking can be severe or hardly noticeable. The Bureau of Reclamation has a procedure that can be used to test if a material is prone to slaking. (Bureau of Reclamation, Engineering Geology Manual, page 80). Rocks whose samples show signs of slaking behavior during testing will need to have special treatments during construction to prevent slaking. Figure 14 shows a sign of a significantly slaked mudstone.

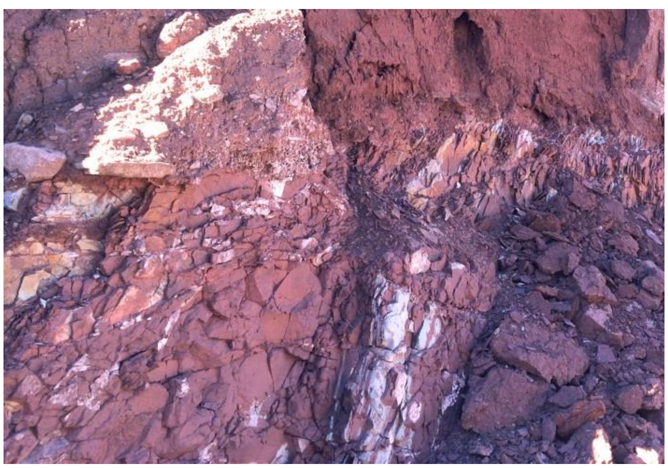

Figure 14 - Effects of Slaking on Mudstone

Soil Foundations

The fundamental characteristics of soil deposits that form dam foundations include plasticity, density, and gradation, which in turn influence the foundation's strength, permeability, compressibility (including settlement and collapse), and dispersiveness/ erosiveness. (See our previous article, "Soil Characterization – Here's the Dirt (Part 1)" for more information.) Problems associated with dams founded on deposits of alluvial, colluvial, eolian and glacial soils are related to the soils' permeability and initial degree of consolidation or density. Low density, soft, or loose soils of all types can settle when extra weight is added on top of them. Differential settlement across a valley with irregular steps in the foundation, or between materials with different densities, can result in cracks in the embankment, and cracks in rigid structures such as outlet works, spillways, valve structures, and vaults. Settlement can also gradually lower the crest elevation, which would reduce the available freeboard. Removal of soft soils or densification of soft soils may be needed at sites where excessive settlement is expected to occur.

Stability is also a concern when constructing a dam on soil. The shear strength of very soft to soft soil is less than that of the compacted material used to build the embankment. This condition results in shear surfaces that will pass through the foundation causing slides, slumps, and cracks in the embankment. To mitigate for this situation, soft foundation soils should be removed. The slopes of the embankment can also be flattened, increasing the footprint of the dam, which moves greater shear strength into the foundation, thereby improving stability.

Deposits of sand, gravel, and cobble are often adequate foundation materials with respect to support of the embankment; however, the major problems associated with these materials include their higher permeability and potentially open matrix. High permeability foundations can lead to excessive seepage, high gradients, and uplift pressures. Open matrix deposits are similar to open fractures in rock and must be isolated from or made filter compatible with the embankment materials they support to prevent internal erosion and/or piping from damaging the embankment or leading to failure.

Seepage and water loss through the foundation can also be an economic problem. Dams that store water intended for irrigation, drinking water, industrial, or commercial uses may not be able to tolerate high water losses. In these cases, porous foundation materials should be removed or treated with low permeable synthetic or clay liners or cutoffs.

Loose, low density, saturated sand, and silt deposits subjected to earthquake loading have the potential to liquefy and lose strength. Liquefaction of foundation soils can lead to slope stability and settlement issues that are similar to the issues related to soft, low density soil foundations. These issues include settlement and loss of crest height that could result in a breach of the dam. Near surface liquefiable material should be removed from the dam foundation. These types of materials should be evaluated by a professional dam engineer.

The above discussion describes only a small selection of foundation problems to be considered in the evaluation and repair of existing dams and the design and construction of new dams. Projects located in varied geologic settings can benefit from the participation of professional geologists, engineering geologists, and/or geological engineers.

Case Histories

QUAIL CREEK DAM AND RESERVOIR

Quail Creek Reservoir is located in the southwestern part of Utah near Saint George. The reservoir is formed by a main dam and dike. On January 1, 1989, the 78-foot-tall dike failed and released 25,000 acre-feet of water causing approximately 12 million dollars in damage (Carlson, D.D. and Meyer, D.F. 1989).

The foundation of the dike was formed by sedimentary rocks deposited in a marine tidal flat environment and consisted of alternating, thin beds of gypsiferous siltstone, sandstone, gypsum, and dolomite (Robert James, J. et al. 1989). The geology was complex, and the rock was described as very weathered, highly fractured, faulted, and folded. **Figure 15** is an aerial photograph after the failure of the dike that scoured soils away exposing the underlying bedrock.

Figure 15 - Quail Creek Dike

Upon first filling of the reservoir, seepage began to flow immediately through the foundation. The response to the seepage was a grouting program and installation of an unfiltered rock toe drain. Three different phases of grouting were done between 1986 and 1988. On December 31, 1988, brown, discolored seepage was observed flowing at about 200 to 300 gallons per minute. A filter was constructed over the seepage area, but ultimately the flow was too great and a backwards piping erosion failure mode caused portions of the embankment to collapse, causing a catastrophic failure.

After the failure occurred, an investigation revealed that although the complexity of the foundation geology was known ahead of time, proper treatment of foundation defects, such as openings and voids along bedding planes, was not used during construction. Figure 16 shows an example of some of the openings along bedding at Quail Creek Dike. In addition to the nature of the foundation defects, the orientation of bedding played important role in the failure. As shown above in **Figure 15**, the orientation of bedding is perpendicular to the axis of the dike which allowed continuous, downstream pathways for foundation seepage.

Figure 16 - Openings along Bedding Planes

Perhaps the most significant deficiency that led to breach of the dike was the failure to provide adequate filters to protect the core of the dam from internal erosion and piping into and along the foundation. The investigation of the failure concluded that several adverse conditions existed that contributed to breach of the dike. The conditions included:

- Open joints along bedding planes were not treated during construction and allowed an unfiltered seepage path with a direct connection with the reservoir.

- Unprotected, erodible core material was placed directly on a poorly treated, weathered, jointed, and (in places) soluble foundation.
- The initial response of foundation grouting to address seepage observed during first filling sealed deeper foundation seepage pathways and forced the seepage closer to the embankment/foundation contact. Seepage along this contact introduced an unfiltered exit through the rock toe drain.

Study of the Quail Creek Dike failure shows the importance of applying the correct design features commensurate with foundation geology and the importance of recognizing how geologic conditions can affect seepage, internal erosion, and piping failure modes.

TARRYALL DAM

Tarryall Dam is located in Central Colorado downstream of the town of Jefferson. It was designed in 1929 as a thin arch dam to be founded on rock.

Figure 17 – Downstream Face of Tarryall Dam from the Right Abutment

The dam has a structural height of 70 feet and a hydraulic height of 38 feet, meaning that the dam itself extends 32 feet below the ground surface as shown on Figure 17. Figure 17 also shows that while the left abutment is a thin arch against jointed rock, the right abutment arch section is supported by a large gravity buttress.

As previously stated, the dam was intended to be a thin arch structure supported by competent abutment rock. Granitic igneous rocks outcrop on both abutments and although moderately jointed, were thought to be suitable for support of this type of dam. However, during the excavation of the cutoff trench to bedrock, the field engineers encountered unsuitable, highly weathered and fractured rock in the right abutment. Realizing this rock would not support an arch, the design was modified to include a large concrete gravity section to provide both increased anchorage for the arch, and a gravity section to prevent overturning or sliding of the dam on this abutment. This configuration worked relatively well for nearly 70 years, until cracking was observed in the arch section monolith joint closest to the gravity buttress section. In 2001, the reservoir was ordered lowered to 5 feet below the spillway to reduce the load on the dam while additional studies were performed. In 2002 the additional studies showed that in fact the dam was unstable at high loading conditions and a zero-storage restriction order was imposed, forcing the reservoir to be fully drained until repairs could be made.

Repair designs focused on providing additional anchorage of the right abutment arch and gravity sections to better support that end of the dam against movement and also to provide additional reaction force for the remaining arch section. A series of eight, multi-strand rock anchors were designed and installed through both the arch section and gravity section to depths up to 111 feet. The anchors secured the dam on the abutment, providing the necessary resistance to overtopping and sliding, and also provided additional reaction for the remaining unanchored arch.

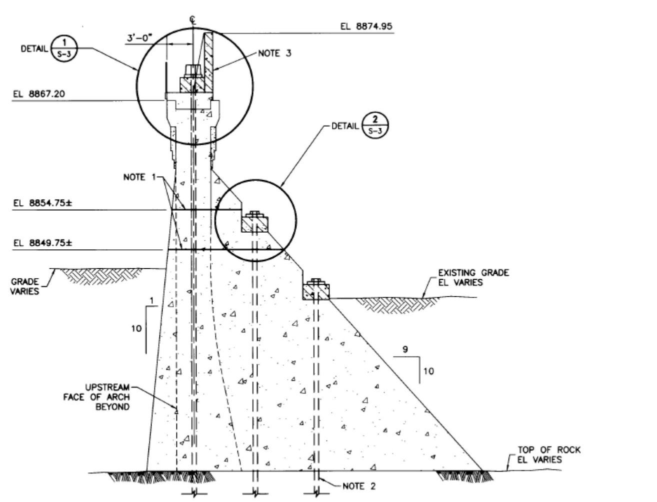

Figure 18 – Detail of Plan for Anchors through Right Abutment Arch and Gravity Sections

Figure 19 – Photo of Anchors Installed through Right Abutment Arch Section.

Conclusion

The benefits of geologic observations made during investigations for new dams or for repairs to existing dams are sometimes overlooked but are essential in preventing costly oversights. After soil and rock types have been identified and geologic constraints defined, the potential issues that may affect dam construction and performance can be evaluated and mitigation strategies developed. In some cases, the potential issues may be minor; in other cases, where geology is complex, problematic, or difficult to characterize, the potential issues may be serious and create inherent uncertainties in how the structure is performing or will perform. This article introduced some basic geologic terminology and principles and provided just a few examples of how geologic conditions might impact a given project. Future articles will be used to delve deeper into these important concepts.

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