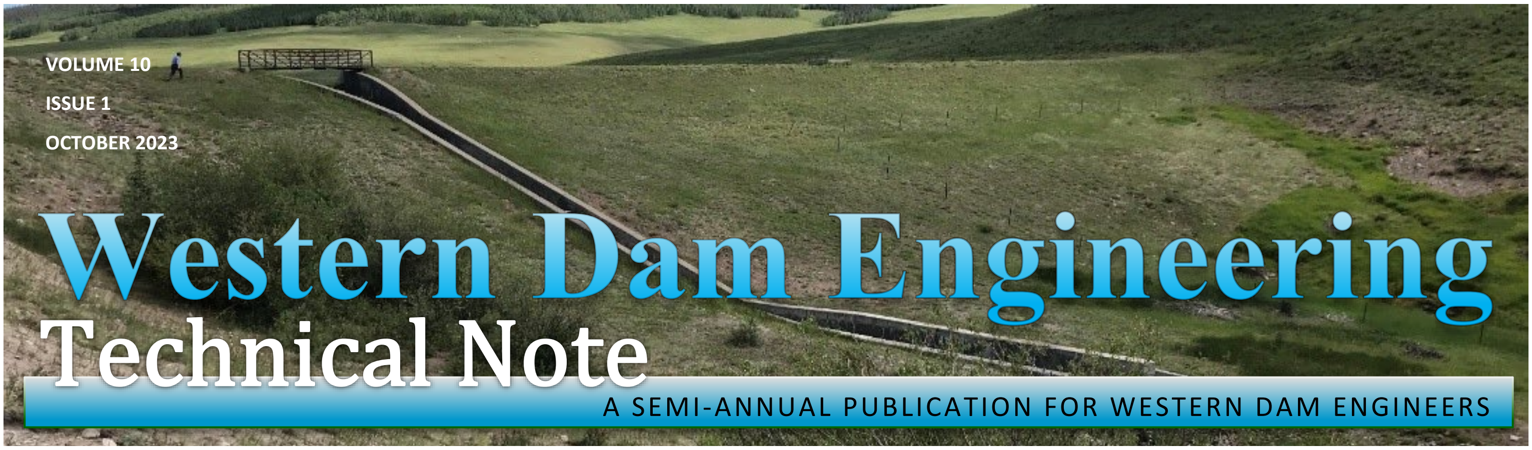

VOLUME 10
ISSUE 1
OCTOBER 2023

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 introducing **foundation preparation and treatment** and **rain on snow modeling**. This newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication provides general technical information focusing on small and medium dams. 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.

Good to Know

Upcoming ASDSO Classroom Seminars:

- *Improving Emergency Operations for Dam and Levee Failures and Incidents, Tampa, FL, April 2, 2024*
- *HEC-RAS 2D, Greenwood Village, CO, May 21, 2024*
- *Dam Construction Inspection, Greenwood Village, CO, October 15, 2024*

Upcoming ASDSO Webinar Dam Safety Training:

- *Spillway Gates and Dewatering Systems - Lessons Learned and Practical Solutions, November 14, 2023*
- *Slope Stability Modeling for Embankment Dams: Planning, Interpreting, and Reporting Results, December 12, 2023*

Upcoming ASDSO Virtual Technical Seminars:

- *Inspection & Assessment of Dams. January 23, 2024*
- *Stability Analysis of Embankment Dams, February 6, 2024*
- *HEC-RAS, March 5, 2024*
- *Seepage Through Earth Dams, June 18, 2024*
- *Basic Soil Mechanics Related to Earth Dams, July 16, 2024*

Conferences:

- *Southeast Regional Conference, Knoxville, TN, April 8, 2024*
- *Dam Safety 2024, Denver, CO, September 22, 2024*
- *Dam Safety 2025, Cleveland, OH, September 21, 2024*

ASDSO Training Website Link

In this Issue

Introduction 1
Foundation Preparation and Treatment 2
Rain on Snow Modeling 9

Foundation Preparation and Treatment

By: Jackson Moloney, EI, and Justin Stoeber, PE

Introduction

The success and safety of a dam relies heavily on the foundation upon which the dam is built. A stable foundation is essential to provide the stability, durability, and overall integrity of the dam structure. This article delves into the different methods of foundation preparation during construction for soil and rock foundations that are implemented for earthen and concrete dams. Although this discussion focuses on foundation preparation for a new dam, the principles are the same for repairing an existing dam, should the repair involve significant excavation (for example, outlet replacement).

Why is Foundation Preparation Important?

The foundation of a dam is the primary support system responsible for distributing the weight of the dam and reservoir load. Foundation treatment is essential to provide a suitable surface contact between the dam and its foundation and provide safety from sliding, uplift pressure on the dam, as well as internal erosion and liquefaction potential of the foundation itself.

Even for small low hazard dams, proper foundation preparation is key to satisfactory long-term performance of the structure. In addition, it is important to take potential future needs into consideration when designing and constructing a new dam, such as increasing the height and reservoir storage capacity. Therefore, potential future modifications should be considered in regard to designing and constructing the foundation.

Methods of Foundation Preparation

Typical foundation preparation methods include excavation, compaction, foundation cleaning, shaping of the foundation with methods such as dental concrete or shotcrete, filling of surface irregularities with slush grout, and treating weak or potentially liquefiable zones. The type and extent of foundation preparation required is highly dependent on the height and type of dam, strength of foundation material (soil/rock), erodibility and permeability of foundation material, compressibility of foundation material, and damsite geometry.

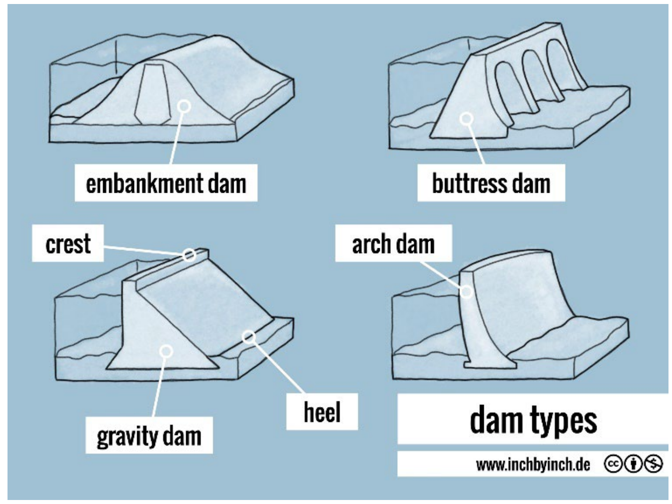

Figure 1: Diagram Depicting Designs for Various Dam Types (Photo courtesy of INCH)

Earth/Rockfill Embankment Dams

Soil Foundations

Prior to construction of an embankment dam, the foundation within the dam's footprint should be prepared to support the loading imposed by the dam and cutoff potential for under-seepage. Organic, soft, collapsible, compressible, loose, or other unsuitable materials as identified by the Engineer in consultation with a professional engineering geologist should be stripped and removed from the foundation area. Irregularities, ruts, and erosion rills should also be removed. Steep slopes may need to be flattened to provide a subgrade suitable for fill compaction and to reduce the risk of arching of the fill or induced cracking in the embankment.

Unsuitable foundation would be defined as a soft or yielding surface identified during proof rolling. If over-excavation of subgrade material is required, embankment fill compatible with the underlying natural foundation material and the overlying embankment may be placed to prepare the foundation to provide uniform support. Fill placed within areas of over-excavation should be selected based on the required strength, permeability, and compressibility of the natural foundation and embankment material to be placed.

Bridging of soft and yielding subgrade materials using coarse ballast rock, or oversized material, may be considered. Bridging results in a firm and unyielding subgrade through particle-to-particle contact and interlocking of the oversized material. However, bridging/stabilization rock beneath a conduit or structure penetrating the dam should be limited to the downstream portion of the dam. Placing oversized ballast material beneath the core of an embankment dam is unacceptable as it may create a seepage path for under-seepage or potentially dangerous seepage gradients that may lead to a failure mode. If over-excavation is required, it is important to maintain cut slopes in the foundation no steeper than 0.5 horizontal:1 vertical (H:V) and flat enough to be stable (USSD 2022).

Prior to placement of embankment fill, the final subgrade should be moisture conditioned, compacted, and proof rolled to demonstrate a firm and unyielding subgrade. Proof rolling is usually completed using a front-end loader with a fully loaded bucket (typically minimum of three cubic yard capacity), off-road articulated truck, or a fully loaded water truck (typically minimum 2,000-gallon capacity). If proof rolling a trench for a new drainage system or outlet conduit, a walk-behind roller or soil compactor is needed.

For earth/rockfill dams, the subgrade is scarified and then moisture conditioned prior to placement of the first lift to enhance bonding of the fill and the foundation material. The depth of scarification is an important variable that needs to be carefully monitored and controlled. The depth of scarification should not extend deeper than about 50 percent of the effective compaction thickness for the material type (ASCE 2013).

Ideally, foundation preparation in soil foundations should always be completed when overnight lows are above freezing. This can be challenging when the foundation preparation is for an outlet replacement or a new drainage system. Often, activities on an existing dam are completed in the fall when reservoir levels are low. Special precautions are needed to prevent the soil from freezing during preparation activities.

Additional excavation may be required if organic material is encountered or yields an unsuitable (soft or yielding) subgrade; over-excavation may be necessary. It is always important to consider this potential in your cost estimation and specifications. Best practice requires that all organic material be removed from the foundation to the extent possible.

Figure 2: Embankment Fill being Compacted after the Foundation was Prepared (Photo courtesy of 'The Constructor')

Rock Foundations

The first step to ensuring a proper foundation for an earthen dam on a rock foundation is to strip the rock foundation of topsoil, compressible soil, loose cobbles, and boulders to expose an intact in situ rock surface. Sharp changes in slopes or vertical/near vertical surfaces should be excavated or backfilled with concrete to facilitate embankment fill compaction. Open joints or fissures should be filled with concrete or grout to prevent potential material transport into the joint or fissure. A rock foundation requires cleaning prior to construction; this is generally completed using air jets or hand tools to remove any loose materials from the surface. Moistening the rock surface also helps maintain moisture in the earthfill when the first lift is being placed.

Figure 3: Compaction of Initial Lift of Fill on a Rock Foundation (Photo courtesy of the US Bureau of Reclamation)

The next step of foundation preparation on a rock foundation is shaping of the foundation. The foundation needs to be shaped to avoid any irregularities and ensure a uniform shape prior to construction. The foundation can generally be shaped adequately by conventional excavation or smooth blasting. If large quantities of rock need to be blasted or excavated, dental concrete can be used to shape the foundation properly (USSD 2022).

Dental concrete is a mix of cement, aggregate, and water that can be used to fill in irregularities in rock surfaces. The application of dental concrete should be used when excessive blasting is required to ensure a uniform shape of the foundation being built upon. Formed dental concrete should be used to shape steep slopes and fill overhangs and should have a minimum thickness of six inches if the foundation rock is weak enough to allow cracking of the thinner concrete under the load of the dam.

Prior to the placement of dental concrete, the foundation surface needs to be thoroughly cleaned and moistened to ensure a good bond between the concrete and the rock. Placed dental concrete should have a minimum 28-day strength of 3,000 pounds per square inch (psi), and the maximum aggregate size should be less than one-third the depth of placement. Finished dental concrete slabs can be roughened with a broomed finish to help ensure the bond between the earthfill and the concrete surface is suitable. Dental concrete should be cured with water for a minimum of 72 hours, so the slab is strong enough to support the placement and compaction of earthfill.

Slush grout is another application for rock foundations. Slush grout is a neat cement or sand cement slurry that is applied to joints or highly fractured rock surfaces in the foundation. A sand cement slurry is generally used for cracks less than one-half inch wide, and a neat cement grout is generally used for cracks greater than one-half inch wide (USSD 2022). Prior to placement of slush grout, the cracks need to be cleaned out using hand tools or air jets and wetted to ensure a solid bond between the rock surface and the grout.

In hard rock foundations, the placement of slush grout can occur at any time prior to fill placement, sometimes immediately before fill placement. In soft rock foundations, the application of slush grout is required immediately before fill placement to ensure no cracking of the grout under the pressure of the fill occurs.

Prior to placement of any fill material, a final cleaning is required to ensure an acceptable bond between the rock surface and the fill material. This final cleaning generally consists of removing any loose material using methods such as water jetting, brooming, or vacuuming. Once the surface is fully cleaned, standing water should be removed from the foundation surface, and the rock should be moisture conditioned to help prevent fill material from drying out during fill placement of the first lift.

Figure 4: Cleaning of a Rock Foundation using an Air Jet (Photo courtesy of the US Bureau of Reclamation)

Placed earthfill should generally be plastic and deformable. Fill materials with a plasticity index range from 16 to 30 (Reclamation 2012b) and moisture contents within two percent of optimum moisture content are generally preferred. Very wet soils should not be used for the first lift as the additional moisture may lead to a subpar bond between the rock and the fill.

Fill compaction methods on a rock foundation depend on the steepness of the surface, quality of prepared surface, and the fill material. A rubber-tired roller or rubber-tired loader with a full bucket should be used to compact the first few lifts above the foundation. Rubber-tired equipment is also used adjacent to concrete surface (e.g., outlet conduit encasement, spillway chute, and stilling basin walls and sloping abutments). The use of a pad-foot or sheep's-foot roller is then used after the fill is sufficiently thick to avoid high points in the rock foundation, and fill can be placed in horizontal lifts, allowing compaction of the lift and avoiding damage to the rock foundation. When placing lifts of fill material on sloping rock surfaces, the feathered edges of the fill can be covered with burlap or another geotextile to limit moisture loss within the fill material.

If fill is being compacted on irregular surfaces or in areas that are not easily accessible using heavy equipment, special compaction such as using a handoperated compactor are used to compact the fill in limited areas. In some cases, it is more cost and schedule efficient to backfill these areas with concrete rather than attempt special compaction techniques. Proper fill placement and compaction procedures should be implemented such that bond is established between lifts. Fill placement and compaction procedures typically includes shallow scarification of the previous lift surface and moisture conditioning before placing the overlying lift.

Concrete Dams

Various types of concrete dams exist; this section details foundation preparation techniques performed for concrete dams, specifically gravity, curved gravity, and arch dams. Concrete dams can be constructed using conventional concrete. However, roller-compacted concrete (RCC) has developed into the primary method of construction for concrete dams.

Gravity dams generally impose high vertical loads on foundation materials. Foundation design for a gravity dam includes evaluating the loads imposed from the dam, the reservoir, and the appurtenant structures to be located within the foundation area.

Concrete arch dams can also impose high vertical loads. However, based on the arch/curved alignment of the dam, a portion of the vertical load is transferred laterally into the abutments. Additionally, a symmetrical, gradually varying foundation profile is important to distribute the stress from the dam and reservoir relatively equally. If construction is occurring in a topographically asymmetrical location, shaping/thrust blocks may be placed for abutment shaping between the dam and foundation.

Rock Foundations

Concrete dam foundations are typically designed to be relatively horizontal in the transverse direction and uniform unless an increased resistance to sliding is desired. If sliding resistance is a design requirement, the foundation surface should be sloped upward (abutment contours converging in the downstream direction) from heel to toe. Foundation surfaces should be stripped of topsoil, compressible soil, loose cobbles, and boulders to expose an intact in situ rock surface. Foundation design, including design of special treatment areas, involves testing and analysis of compressive strength and rock quality with the objective of establishing a foundation grade in fresh to moderately fresh rock The design should establish the foundation properties for use in the field to identify the foundation surface preparation.

Blasting, rock hammer, and/or grinding heads can be used to remove sharp offsets or irregularities in the foundation surface; however, caution must be exercised when blasting as damaging the foundation rock may require extensive efforts to remediate. The exposed surface is usually uneven due natural roughness of the rock surface or roughness from blasting and can be beneficial for increasing the shear strength at the foundation contact. Smooth planar surfaces are not expected for a concrete dam foundation, with the exception of dental concrete placed to even out overhangs or large variations in the finish surface that could affect foundations stress distribution into the dam.

Figure 5: Drilling Blast Holes to Remove a Rock Overhang (Photo courtesy of the US Bureau of Reclamation)

Rock type is also a major consideration in the design of a dam foundation and surface treatment. Rock foundations consisting of igneous or metamorphic rock have some inherent benefits depending on the joint/fracture frequency, joint/fracture spacing/orientation, and condition of joints/fractures. Sedimentary rock foundation can range from very good to poor. An example of poor sedimentary rock foundation would be relatively flat lying to dipping downstream smooth bedding planes. Foundation support issues pertaining to sedimentary rock material include:

a) weak shear strength along bedding plans (e.g., claystone, shale, siltstone etc.);
b) seepage along bedding planes;
c) high permeability beds (e.g., weakly cemented conglomerate, highly fractured sandstone etc.); and
d) deterioration of the foundations surface after exposure to the environment. The use of shear keys with passive wedges in the foundation rock may be required to improve the shear resistance against sliding along the foundation contact of sedimentary rock with weak shear strength. Surface deterioration from exposure to air (slaking of claystone and shales) or physical deterioration from construction equipment (e.g., excavation equipment, foundation grouting equipment) can be limited with placement of shotcrete or a “mudmat” over the exposed foundation for the time interval between excavation and dam construction.

Other challenges for foundation design and surface treatment include soluble material (e.g., gypsum) and expansion of shale beds after removal of overburden to design grade due to unloading from foundation excavation. Field conditions can and will vary, and close coordination with the designer and geologist/geotechnical engineer is a key component of dam construction.

Surface preparation and treatment of the dam foundation for a concrete dam involves dental concrete at most dams. The application of dental concrete is used to treat faults/shear zones, seams, or shattered or inferior rock. The weak or affected material is removed, and the excavation is then backfilled with dental concrete.

General rules for how deep transverse seams should be excavated for dental treatment that have been formulated based on actual foundation conditions and stresses in dams are as follows (Reclamation 2012a):

$$d = 0.002\, bH + 5 \text{ for } H \geq 150 \text{ ft}$$
$$d = 0.3\, b + 5 \text{ for } H < 150 \text{ ft}$$

Where:
H = height of dam above general foundation level in feet
b = width of weak zone in feet
d = depth of excavation of weak zone in feet

Typical Specification Examples for Foundation Preparation:

Slush Grout Placement	Typical Requirements: Thoroughly clean all fractures/cracks of all loose material to minimum depth (e.g., minimum treatment depths depend on fracture/crack width) by using high-pressure air or other methods approved by the Engineer. Wet surfaces immediately before placement. Do not place grout when freezing conditions are expected or protect from freezing conditions while grout is curing. Place in fractures/cracks only; avoid spillage and feather edges.
Proof Rolling	Minimum number of passes with specified equipment to identify soft areas that will not support future loading without excessive settlement. Over-excavate unacceptable areas identified by the proof roll and replace with suitable compacted material.
Rock Shaping	Shape and grade using mechanical and hand equipment. Drilling and blasting typically not allowed but may be acceptable under certain conditions. All equipment, techniques, and procedures subject to approval. Precludes work methods causing damage.
Dental Concrete Placement	Place as required to form a tight, unfractured surface against which concrete or compacted fill lifts can be satisfactorily placed. Wet rock surfaces before placement. Placement and Curing: Same as for conventional concrete. No overlying fill placed until cured sufficiently (e.g., 3 days minimum). Finish: Typically broomed.
Final Rock Cleaning	Just prior to placing fill materials, clean the rock surface and remove excess slush grout, dental concrete, and any remaining loose, shattered, or disintegrated material, and clean the surface with jets of air under high pressure. Final cleanup of the rock surface is subject to approval by the Engineer.

Prior to placement of concrete, it is essential that proper cleaning techniques are performed on the foundation to remove any loose sediment or standing water that may inhibit the quality of the bond between the foundation rock and the placed concrete. Improper cleaning of the foundation can reduce the compressive and shear strength at the contact, forming a high permeability path for seepage and internal erosion. Rock foundations should be cleaned by prying any loose or weak rock from the foundation using hand tools, using an air/water jet to remove all loose material missed by machine stripping, and using a vacuum to remove any standing water. Immediately prior to placement of concrete, the rock surface should be moistened with water to facilitate bonding between the foundation surface and the concrete.

Figure 6: Use of Dental Concrete to Treat a Surface Irregularity (Photo Courtesy of the US Bureau of Reclamation)

In the event that faults/shear zones and seams in the foundation rock that are exposed in the excavation contain erodible material, cutoffs may need to be installed to prevent against internal erosion. Cutoffs should be keyed a minimum of one foot per Reclamation recommendations 2012a) into the sound rock and backfilled with concrete prior to initiating construction. For large dental concrete placement areas (on the order of 10 cubic yards [cy] or larger), the placement of backfill concrete on the dental concrete is acceptable, but the dental concrete should be cured properly before any backfill concrete is placed upon it to minimize cracking or shrinking of the backfill concrete.

Conclusion

Foundation preparation is a critical component of dam construction that is focused on providing the support required for overall stability, safety, and longevity of these essential structures. Foundation design consists of developing proper excavation limits, shaping of the foundation, and dental concrete placement for the filling of surface irregularities, and/or treating foundation areas insufficient for support of the dam.

As the demand for water resources, flood control, and renewable energy continues to rise, the proper preparation of dam foundations remains essential for sustainable and resilient infrastructure development. The key consideration in foundation design and treatment for dams is that the actual geotechnical/geologic conditions are not fully known until the foundation is exposed. Surficial mapping of the exposed foundation and a final evaluation of the exposed conditions must be prioritized so that adjustments needed to adapt the dam foundation design intent can be implemented, and this in turn allows engineers to confidently build and maintain dams that provide reliable services while minimizing the potential for failures.

References

[1] American Society of Civil Engineers (ASCE). 2013. Foundation Treatment for Rockfill Dams. October.

[2] United States Bureau of Reclamation (Reclamation). 2012a. Foundation Surface Treatment. Chapter 3, Design Standards No. 13.

[3] Reclamation. 2012b. Foundation Preparation, Treatment and Cleanup. Chapter 21, Design Standards No.13.

[4] United States Society on Dams (USSD). Guidance for Surface Preparation of Dam Foundations. April 2022.

[5] Association of State Dam Safety Officials (ASDSO). Damfailures.org Case Study: Quail Creek Dike, Utah. 1989. https://damfailures.org/case-study/quail-creek-dike-utah-1989/

Case Study: Quail Creek Dike

Quail Creek Dike was a 1,980 foot long, 78-foot-high zoned earthfill structure that was completed in 1985 in Washington County, Utah. Prior to construction, a foundation investigation encountered low permeability gypsiferous bedrock below 10 feet of weathered bedrock and permeable sandstone was identified in the left abutment. As the reservoir filled, seepage reaching 5 cubic feet per second (cfs) was observed along the downstream left toe of the dike.

In 1986, foundation grouting to reduce the seepage flow at the toe of the embankment was undertaken. During the foundation grouting, several "open conduits" in the dike foundation were encountered, leading to large grout takes (on the left abutment a total of 805.5 sacks of cement were injected in a 5-foot length of a grout hole in the foundation).

As the reservoir was refilled in June 1987, seepage at the downstream toe began to increase, and a two-foot diameter sinkhole was discovered at the toe of the dam. In an effort to control seepage and erosion of foundation material, a graded filter was installed over the sinkhole, and a second foundation grouting program was implemented. The second grouting program experienced large grout takes and reduced seepage to about 1 cfs with the reservoir at full pool.

In September 1988, a third round of foundation grouting was implemented; during grouting, a major opening in the foundation was encountered. Extended grouting of the large void in the foundation was unsuccessful to achieve grout closure of the feature, and concrete, sand, and gravel were pumped into the hole in an effort to plug the void.

On the morning of December 31, 1988, turbid seepage was observed at the downstream toe of the dike on the order of 300 gallons per minute (gpm). Efforts throughout the day and night to monitor and mitigate the seepage and accompanying void proved unsuccessful, and the direction of the seepage flow shifted from horizontal to vertical, leading to an evacuation of the public downstream of the dam. At approximately 12:30 a.m. on January 1, 1989, Quail Creek Dike failed and released approximately 25,000-acre feet of water downstream. Several bridges, roads, and structures were damaged in the process, resulting in approximately $12 million in damages from the breach (Association of State Dam Safety Officials [ASDSO] 1989).

Figure 7: Quail Creek Dike Breach Photos (Independent Dam Failure Review Team, Quail Creek Dike 1989)

After an independent review of the failure, it was determined that the failure had resulted from flow of water through an unidentified karstified gypsum unit beneath the embankment and improper preparation of the foundation prior to the placement of embankment materials. Embankment materials were also placed on the foundation without appropriate protection against seepage moving through the karstified gypsum unit. The review team concluded that if the materials had been protected by proper drains, filters, and foundation surface treatment, the failure would not have occurred. As a result of this failure, dam safety regulations in Utah were strengthened, and foundation surface treatment guidelines were created to prevent future catastrophic dam failures (ASDSO 1989). Refer to the case study on DamFailures.org for more information on the failure of the Quail Creek Dike.

"If you can't afford to build it right the first time, you can't afford to build it twice."

-Matt Lindon

Rain on Snow Modeling

By: Erik Sutherland, PE

Introduction

Rain on snow (ROS) events are due to a meteorological phenomenon that occur when warm rain falls onto an existing snowpack. This interaction between rain and snow has gained increased attention in recent years due to climate change and its potential to cause various environmental and societal impacts, including flooding, avalanches, altered hydrology, and ecological disruptions.

Modeling these interactions is important for understanding and predicting the outcomes of ROS events, especially in regions where snowmelt-driven runoff plays a vital role in water availability and in flood peak and volume estimation. This article will introduce ROS modeling and explore its significance, approaches, and challenges. This article is not intended to be a comprehensive instruction manual but rather an introduction to the concepts and tools available for ROS modeling.

The Significance of Rain on Snow Events and Modeling

ROS events can have significant consequences, particularly in regions where snow accumulation is common during the colder months. When rain falls on an existing snowpack, several factors come into play:

1. **Enhanced Snowmelt:** Rainwater infiltrates the snowpack, increasing its temperature and accelerating the melting process. This can lead to a rapid release of water, or precipitate, potentially overwhelming local drainage systems and causing flooding. By understanding the interactions between rain and snow, models can help forecast potential flood events and inform emergency preparedness and response efforts.
2. **Runoff Generation:** As the snow melts, the water can pool on the surface, creating a layer of slush and/or contribute to shallow flooding. Accurate predictions of snowmelt and runoff are important for managing water supplies, reservoir levels, and irrigation systems in regions reliant on snowpack as a water source.
3. **Avalanche Risk:** The added weight of rainwater can increase the risk of snowpack instability, potentially triggering avalanches. This can pose a threat to both human safety and infrastructure. Snow models (rather than the hydrologic models discussed herein) can aid in assessing avalanche risk by considering the impact of rainfall on snowpack stability.
4. **Ecological Impacts:** ROS events can affect ecosystems by altering soil moisture, promoting erosion, and disrupting wildlife habitats. Models provide insights into how ecosystems may respond to changing precipitation patterns, helping researchers study the ecological consequences of these events.

Where and When to Use Rain on Snow Modeling (in Dam Safety)

In terms of dam safety, the consequences associated with ROS events are most significant when the design flood event, whether that is a frequency storms or the Probable Maximum Precipitation (PMP), falls on existing snowpack. While it is extremely unlikely that the PMP would occur during snow melting season for most of the United States, more frequent ROS events have a long history of contributing to flooding that has the potential to threaten property or human lives.

Li et al. (2019) reviewed numerous case histories of ROS events across the United States between 1950 and 2013, and their research indicated that impacts from ROS events are felt mainly in the major western mountain ranges (Cascades, Sierra Nevada, and Rockies), the Upper Midwest, Northeast, and lower Appalachia regions of the continental United States, as shown in **Figure 1**. ROS events typically occur in the fall and winter for the coastal regions and in the spring for the high mountains in the west. While a significant portion of large/extreme runoff days tend to be ROS-related, a relatively small portion of the total runoff is attributed to the actual ROS process, but rather intense rainfall or radiation-driven snowmelt, even on ROS days (Li et al. 2019).

Runoff during a ROS event is typically driven by precipitation (atmospheric rivers) along the west coast and by snowmelt in the rest of the regions. Precipitation-driven runoff tends to result in greater peak flows in shorter durations, which is often more important to understand for safe dam operations than longer duration snowmelt floods. Therefore, extra consideration should be given to ROS events for locations along the west coast (specifically the Pacific Northwest).

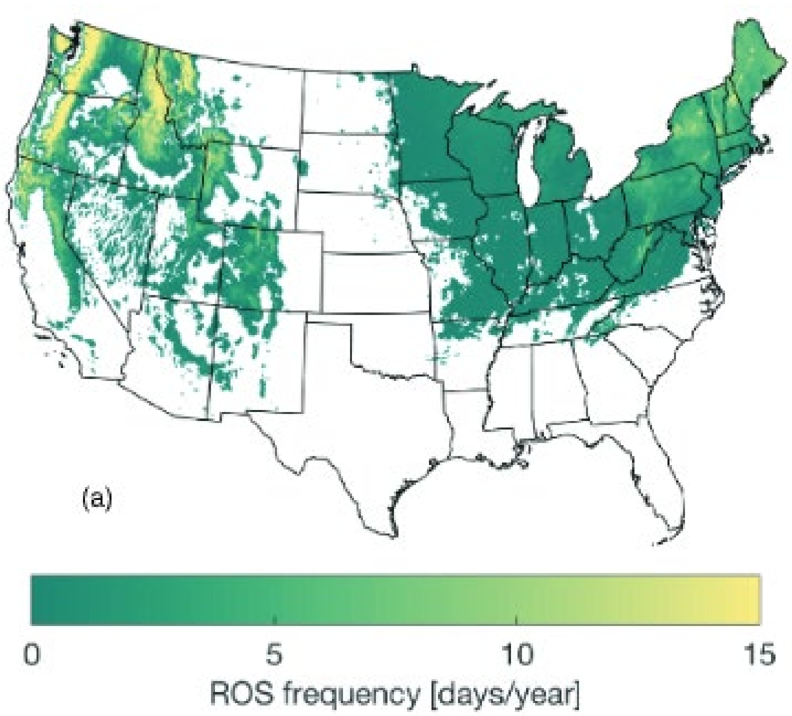

Figure 1: ROS Frequency for Continental United States (Li et al. 2019)

Guidance on ROS hydrology is still being developed for much of the United States. For example, the Dam Safety branch of the Colorado State Engineer's Office recently updated their hydrology guidelines; however, there is limited discussion on ROS considerations. The SEO guidelines state that ROS events only need to be considered on a case-by-case basis for low hazard dams, especially where observed flood records indicate ROS is relevant to design flood production (SEO 2022).

For significant and high hazard dams, where the design flood is a much less frequent event, studies have shown that ROS events typically do not control design flooding scenarios, and, therefore, do not need to be considered. It is envisioned that as the industry's understanding of these events continues to grow, more states (particularly in the Pacific Northwest) will develop a more analytical methodology for ROS analyses.

Modeling Methodologies

Accurately modeling ROS events requires accurate meteorological data (including temperature, precipitation rates, solar radiation, wind speeds and patterns, etc.). These inputs help determine the type of precipitation (rain, snow, sleet) and the intensity in which it will occur.

Additionally, ROS models take into account various properties of the snowpack, such as melt rates, density and temperature gradients, and water content. These characteristics influence how the snowpack will respond to the presence of rain. Modeling the hydrological process associated with ROS events can be achieved using a hydrologic model such as the United States Army Corps of Engineers (USACE) Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) [USACE 2023b]. Other models (including but not limited to: MIKE SHE, EPA SWMM, WinSRM, SWAT) allow the user to model ROS processes; however, this article focuses on HEC-HMS due to its availability and widespread use across the industry.

HEC-HMS currently has three methods to model ROS events: the Temperature Index Method, the Radiation-Derived Temperature Index (Hybrid) Method, and the Energy Balance Method. Each of the methods have varied levels of complexity and required input parameters. A general description of these methods and their required inputs is presented below, and a summary of the energy sources used by snowmelt routines in HEC-HMS is presented in **Figure 2** (USACE 2023a):

Temperature Index (TI): This is the simplest method in HEC-HMS to model ROS events, and its flexibility allows for the easiest model calibration relative to the other methods described herein. This method relies solely on air temperature to estimate melting potential and is the most widely used method due to its simplicity.

Radiation-Derived Temperature Index (RTI or Hybrid Method): In addition to the air temperature, this method includes calculations of short-wave radiation and long-wave radiation to estimate melting potential.

Energy Balance (EB): This is the most complicated ROS modeling approach in HEC-HMS and utilizes a complete energy balance to simulate the ROS process. This method is used when air temperature and radiation are not the primary sources for snowmelt (rather ground heat, wind, and precipitation, or a combination of energy sources as shown in **Figure 2** and **Table 1.**

The energy balance method is the preferred method for Federal Energy Regulatory Commission (FERC) projects; however, it requires a large number of accurate meteorological inputs that are typically not readily available. Therefore, FERC provides guidance on simplifications that can be made, leaving the main required input variables as follows (FERC 2001):

- Snowmelt temperature
- Temperature sequence (time-series)
- Wind speed (or wind time-series)
- Rainfall sequence (time-series)
- Snowpack water equivalent (SWE) - snow data can be obtained from the following sources (USACE 2023a):
  - **National Oceanic and Atmospheric Administration's (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC)** provides modeled snow data output from the SNOw Data Assimilation System (SNODAS) model from October 2003 through the present (https://www.nohrsc.noaa.gov/).
  - **The Natural Resources Conservation Service (NRCS)** owns and maintains a network of snow observation sites, SNOw TELemetry (SNOTEL). The NRCS also regularly conducts manual snow surveys throughout the mountainous regions of the western United States (https://www.nrcs.usda.gov/wps/portal/wcc/home/). SNOTEL data collection began in 1978 at some stations and extends through the present.
  - **United States Army Corps of Engineers Snow Surveys**
  - **Remote Sensing**
  - **Passive Microwave Measurements** archived at the National Snow and Ice Data Center (NSIDC) (https://nsidc.org/home)
  - **Daymet** is a collection of algorithms and computer software designed to interpolate and extrapolate from daily meteorological observations to produce gridded estimates of daily weather parameters for North America from 1980 to the present (https://daymet.ornl.gov/).

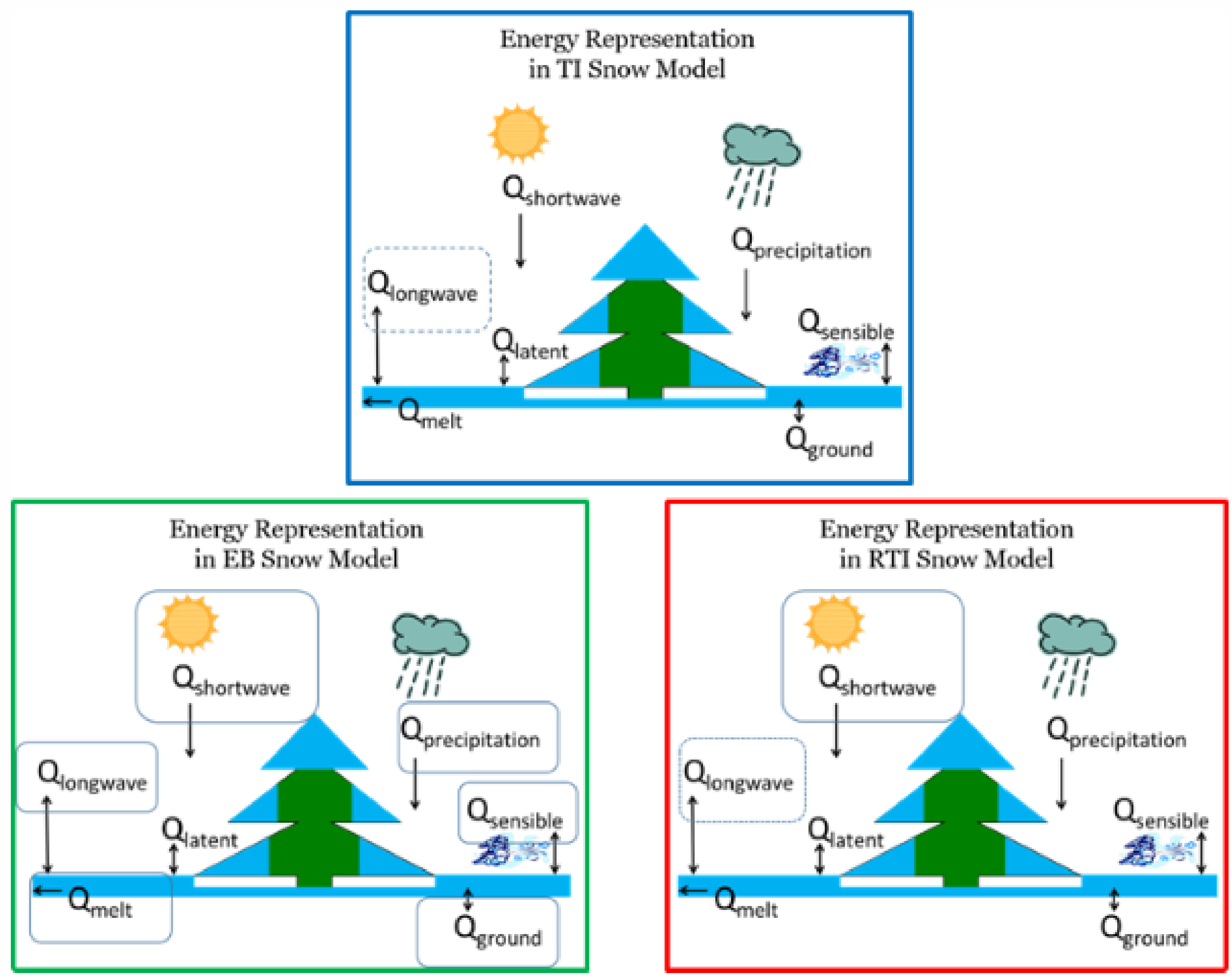

Figure 2: Energy Sources (Q) Used by Snowmelt Routines in HEC-HMS (USACE 2023a)

A list of required input parameters for the Temperature Index Method, including a brief description and typical values recommended by the HEC-HMS user's guide (USACE 2023a), is presented in **Table 1**. For additional information regarding the input parameters or information on input parameters associated with the Hybrid or Energy Balance Methods, refer to the HEC-HMS user's guide (USACE 2023a) and *EM 1110-2-1406: Runoff from Snowmelt* (USACE 1998).

Table 1: HEC-HMS Input Parameters for Temperature Index ROS Modeling (USACE 2023a)

Input Parameter	Description	Typical/Suggested Values
Lapse Rate	Rate at which temperature drops with increasing elevation.	3.6 degrees Fahrenheit (°F)/1,000 feet (but decreases at altitude)
Discrimination Temperature (PX Temperature)	Temperature that determines whether the precipitation falls as rain or snow.	User selects a temperature from within a range of 32°F – 35°F

Input Parameter	Description	Typical/Suggested Values
Base Temperature	Temperature at which snow melts. If the air temperature is greater than the base temperature, snow will melt.	32°F
Antecedent Temperature Index (ATI) Meltrate Coefficient	Used to adjust the ATI melt rate calculated during the previous timestep.	0.98
Wet Meltrate	Snowmelt that is precipitation induced – when precipitation is falling at rates greater than the Rain Rate Limit. Can be set to a constant value or an annual pattern.	0.08 to 0.15 inches/°F-days
Dry Meltrate	Snowmelt during warm periods with no precipitation. Can be set to a constant value, annual pattern, or ATI – meltrate function.	0.015 to 0.15 inches/°F-days
Rain Rate Limit	Determines whether the dry meltrate or wet meltrate is used.	0.25 to 1.0 inches/day
Cold Limit	Used to reset the cold content when a sufficient amount a new snowfall accumulates.	0.2 inches/day
Coldrate Coefficient	Represents the influence of air temperature on the internal snowpack temperature.	0.2 (shallow snowpacks) to 0.5 (deep snowpacks)
Water Capacity	The maximum amount of liquid water that can be held in the snowpack before runoff occurs.	3% - 5%
Groundmelt	Rate at which snow melts due to heat from the ground.	0 inches/day

Effects of Rain on Snow

The HEC-HMS user's guide (USACE 2023a) provides tutorials on setting up and running a snowmelt model. The tutorial for the Truckee River and South Lake Tahoe explores the process of setting up and running a ROS model using each of the three snowmelt methods that HEC-HMS has to offer.

A comparison of the observed runoff at South Lake Tahoe was made to the modeled runoff using each of the three snowmelt methods, as well as no snowmelt, and is presented in **Figure 3**. The figure indicates that for this scenario the Temperature Index method generally matches the observed data the closest and that no snowmelt results in much "flashier" flooding where peak discharges are higher, but the duration of flows are much shorter. This is likely due to precipitation infiltrating and being stored in the snow (and converted to ice) and released over time as the snow/ice melts.

This modeling exercise illustrates that ROS modeling has the potential to increase or decrease peak discharges at different points in time, it delays runoff generation, and increases runoff volume.

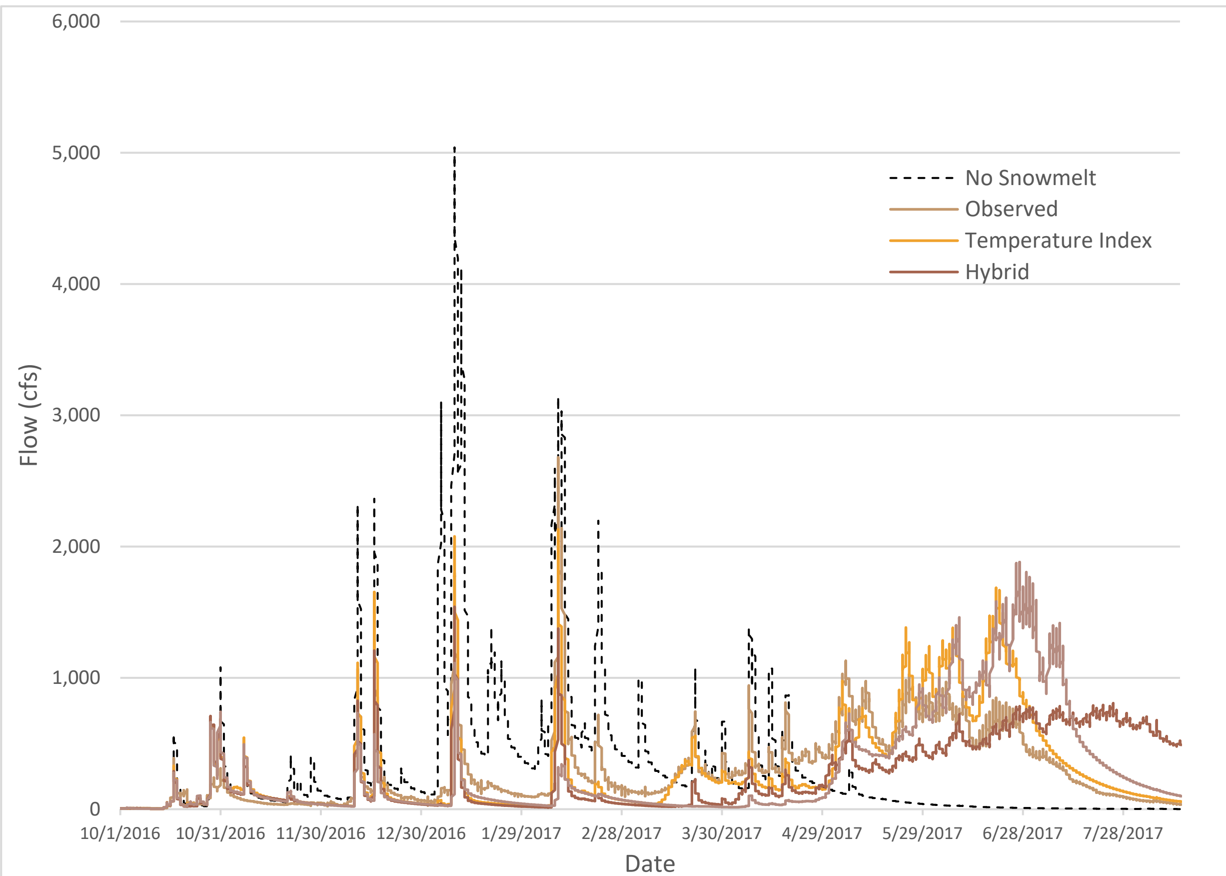

Figure 3: Comparison of Rain on Snow Event Methodologies to Observed Flows

Challenges and Future Directions

Despite significant advancements, ROS modeling still faces challenges due to the complexity and variability of natural systems and the sensitivity to some of the variables. Improving the accuracy of meteorological inputs, enhancing our understanding of snowpack processes, and incorporating real-time data into models are ongoing areas of research.

As climate change continues to influence precipitation patterns and temperatures, the dynamics of ROS events will continue to evolve. Models will play a crucial role in helping us anticipate and adapt to these changes, mitigating potential risks and maximizing the benefits of snow-covered regions.

As states in the Cascades, Sierra Nevada, and Rocky Mountains, as well as the Upper Midwest, Northeast, and lower Appalachia regions of the continental United

States continue to develop procedures for analyzing ROS events, it will be important to consider the effects that ROS can have on developing design hydrology for dams and other water resources infrastructure, particularly when the design flood event has the potential to occur while snow is on the ground. ROS hydrology appears to have a greater impact in coastal states; however, the magnitude of impact is yet to be defined and more studies are needed.

In conclusion, ROS modeling provides a great framework for understanding the interactions between rain and snow and their broader implications. By advancing our understanding of this delicate balance, researchers and decision-makers can make more informed decisions to manage water resources, predict and mitigate flooding, and preserve the ecosystems of cold and mountainous regions. As our knowledge and modeling capabilities improve, we are better equipped to address the challenges posed by ROS events in an ever-changing world.

References

[1] Federal Energy Regulatory Commission (FERC) 2001. Engineering Guidelines for the Evaluation of Hydropower Projects – Chapter 8: Determination of the Probable Maximum Flood.

[2] Li, D., Lettenmaier, D. P., Margulis, S.A., & Andreadis, K. (Li et al.). 2019. The role of rain-on-snow in flooding over the conterminous United States. Water Resources Research,55, 8492–8513. https://doi.org/10.1029/2019WR024950

[3] United States Army Corps of Engineers (USACE). Engineer Manual 1110-2-1406: Runoff from Snowmelt. 1998.

[4] USACE. 2023a. HEC-HMS Tutorial and Guides – Modeling Rain-on-Snow Events. https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/modeling-snowmelt/modeling-rain-on-snow-events

[5] USACE. 2023b. Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) version 4.11.