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Reclamation's Seepage Barrier Experience - A Cursory Scoping Study

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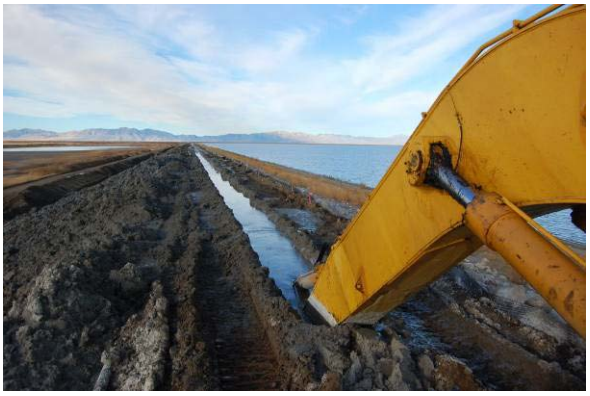

A. V. Watkins Dam Cutoff Trench Installation, Fall 2008

U.S. Department of the Interior
Bureau of Reclamation
Materials Engineering and Research Laboratory
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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Reclamation's Seepage Barrier Experience - A Cursory Scoping Study

Introduction

The purpose of this report on seepage barriers is to develop a cursory scoping study evaluation for the long term performance characteristics of cutoff walls used in dams. Cutoff walls are a type of seepage barrier structure designed to reduce the flow of water through or around a dam.

A reading of "Findings of Case Histories on the Long-Term Performance of Seepage Barriers in Dams" by John Rice and J. Michael Duncan, 2010, and input from TSC designers raised our curiosity about Reclamation's cutoff wall performance experience. Rice and Duncan's papers have identified problems affecting performance including seepage water flow path changes and downstream wall deflection. A case history of some of Reclamation dams and features was assembled to document the types of applications and issues involving our cutoff walls and seepage barriers.

Because Reclamation has such a large inventory of dams, the results of this study could affect how we construct Reclamation's cutoff structures. Identifying those techniques which are most effective for seepage reduction will help Reclamation improve the performance of its embankment structures.

This report will summarize the results of the scoping study including any ideas for future research.

Conclusions

Several Reclamation embankments have benefited from the installation of contemporaneous and post-construction cutoff wall installations. They appear to be well engineered and have generally performed as designed and have not caused problems.

In general, cutoff wall applications in Reclamation dams designed to improve the foundation and prevent seepage water from flowing have been successful. They have been applied to both foundations and abutment seepage problems. In most cases seepage barriers were not designed to improve the performance of the embankment and in a small number of cases minor seepage and deflection problems may result.

New applications of cutoff walls in high risk dams such as at A. V. Watkins Embankment Dam will require active investigations and innovative construction techniques as well as materials investigations to ensure an effective long lasting barrier application is feasible.

All high risk embankments with a regular filling pattern and low freeboard may benefit from a seepage barrier application (Safety, Security, and Law Enforcement).

All embankments with potential seepage, internal erosion, solutioning, and piping problems, i.e., Horsetooth, Merritt, Alcova, Rudi, etc, may benefit from a seepage barrier application.

Recommendations

Consider large grout and slurry losses during cutoff wall construction a warning and resolve any foundation issues with immediate evaluation and action; amend specifications to accommodate a solution:

- Design specifications to pursue the design grade when installing cutoff walls in foundations.
- Design specifications to anticipate foundation defects and be prepared to fully address any defects upon foundation excavation prior to clean-up and embankment placing operations.
- Use remedial grouting technologies to improve foundation /embankment contacts and ensure no erosion occurs at foundation / embankment contacts.
- Find solution cavities in advance of construction and pre-grout.

Consider low strength concrete walls that match the deformation properties of the embankment.

Continue to improve cutoff wall design to prevent defective joints between adjacent panels.

Install proper flow measurement systems and piezometers and monitor them to determine the effectiveness of the seepage barrier system.

Continue to require regional and local exploration of dam site geology as well as detailed geologic maps of cleaned firm foundation surfaces prior to construction.

Findings

Cut-off walls or seepage barriers are frequently used to slow down or prevent seepage of water through and/or around dams. They can be installed during construction to mitigate difficult foundation problems such as seepage pathways through pervious materials and structural, weathering, and morphological pathways in foundations. If

the problems are identified during preconstruction and construction investigations, seepage problems can be addressed during foundation excavation and preparation.

Cutoff walls are also installed after construction and first filling as well as after long periods of service to reduce the flow of unintended seepage through the foundation and abutments. Typically, experience shows that a cutoff wall is installed in the embankment to penetrate the foundation seepage pathway to reduce excessive seepage. Post-construction installation of shallow reinforced cutoff walls is also being considered to address vulnerabilities in high risk embankments.

There are a number of techniques for the construction of cut-off walls including concrete, cement-bentonite slurries, and cement grouting as well as secant walls, deep soil-mixed walls, sheet pile walls, upstream seepage blankets, and compacted earth. They are thought to be a long term solution to blocking seepage, but Rice and Duncan's research suggest cutoff walls may not as be effective over the long term and potentially may cause additional failure modes to develop caused by differential water pressure across the barrier, deformations, and increased gradients through and around the barrier.

Appendix A documents several Reclamation applications of cutoff walls and provides a description of the geologic setting of the dam site. A case history was developed for several dams from Reclamation's Comprehensive Facility Review (CFR); Evaluation of Design, Analysis, and Construction Reports, Rice's PhD thesis, and Rice and Duncan, 2010, as well as other sources. Rice and Duncan provide independent analysis of seepage barrier applications and they highlight performance issues for several Reclamation and other agencies dams. The references from these sources are considered an up to date comprehensive literature review of seepage barriers and cutoff wall applications.

Reclamation Dams or Features with Cutoff Wall Applications

- Fontenelle
- Navajo
- Virginia Smith
- New Waddell
- Meeks Cabin
- Jackson Lake
- Twin Buttes
- A. V. Watkins
- Diamond Creek Dike
- Bradbury

Results

Seepage barriers appear to increase reliability of the listed dams and mitigate seepage problems. The Fontenelle, Navajo, Virginia Smith, New Waddell, Meeks Cabin,

Jackson Lake, and A.V. Watkins Dams seepage barriers appear to be effectively reducing flow. The Twin Buttes Dam application has not yet been fully tested by full reservoir conditions due to drought. Rice, 2007, documents evidence of increased hydraulic gradients around the barrier at Navajo Dam.

According to Rice and Duncan, 2010, seepage barriers add potential mechanisms for internal erosion and piping. Seepage barriers also appear to increase water pressure and hydraulic gradients. At Fontenelle Dam evidence indicates concrete diaphragm wall defects are causing increased seepage. Rice indicates there is also data supporting increased seepage due to fractured and weathered foundation conditions. Fontenelle Dam almost failed due to foundation seepage during first filling in September 1965.

Discussion

Experience

The case histories indicate that seepage barriers were both installed anticipating foundation seepage problems or after construction in response to seeping, eroding, and/or unstable foundations. The seepage walls typically penetrate the embankment and the foundation to firm rock cutting off flow in pervious rock or alluvium.

In general, the reviewed seepage barriers were not designed to improve the performance of the embankment except at the foundation barrier contact. In most instances, the reliability of the dam and the integrity of the foundation were improved and the seepage problem mitigated.

However, new research has shown that the seepage barriers may affect embankments with increased water pressures and gradients around barriers which are usually anticipated in the design, but the long term effects are not understood. Monitoring of the embankment structure during a range of reservoir conditions can provide insights into seepage barrier performance.

There is no evidence that the installation of seepage barriers in Reclamation embankments increase the likelihood of internal erosion and piping of the embankment. However, seepage barriers at Fontenelle and Navajo Dams likely increased flow around the seepage barrier.

At Fontenelle Dam, evidence indicates decline of seepage resistance due to defects in the cutoff wall joints and fractured and weathered foundation rock in contact with the embankment (Rice, 2007). Small deformations in the cutoff wall have been documented with the extensive monitoring system in place and do not appear to be causing excessive seepage.

At Navajo Dam, the installation of the wall appears to reroute flow from the embankment and likely deeper into the foundation. According to the CFR, the

performance of the seepage barrier is unknown due to poor performance of the piezometer network. Also, large slurry losses were documented at the foundation embankment contact during construction.

Anticipating foundation problems during construction such as at Virginia Smith, Jackson Lake, and New Waddell Dams appears to an effective way to mitigate seepage problems.

Constructing seepage barriers of low-strength concrete or soil-cement-bentonite fill which matches the deformation properties of the embankment materials appears to resist cracking, and remains intact and somewhat flexible.

Standard practices

The quality of the foundation rock of major embankment structures should be fully understood and any foundation defects improved by removal or pre-grouting of unsound, porous, or unstable rock; ground improvement to assure the foundation is firm and impervious; as well as utilize state-of-the-art specifications to assure good foundation and embankment material construction methods and quality assurance prior to construction

Design specifications ensure that embankments are not built on pervious or defective foundation materials.

Design specifications to reduce the uncertainty of the harmful properties of in-situ firm foundation materials, especially after foundation excavation to firm rock.

Partners

We should partner with Reclamation's Dam Safety and Security Offices. Many issues including foundation seepage, piping, erosion, and carbonate foundation dissolution and increasing the resistance of embankments to head-cut erosion after potential blast scenarios are currently being studied.

We should partner with the U. S. Army Corps of Engineers (USACE), Federal Energy Regulation Commission (FERC), National Resources Conservation Service (NRCS) and state division of water resources offices (DWR). These agencies have many dikes, levies, and embankments with the same Dam Safety and Security issues as Reclamation. Reclamation's experience at A. V. Watkins is a good example of an embankment built on soft sediments with stability and seepage problems that required emergency action. The dam's efficiency and stability were improved with a bentonite slurry wall penetrating defective foundation material. The USACE has many embankments, dikes, and levies that may also require innovative foundation stabilization and seepage barrier solutions.

The Future

Cutoff walls will likely be installed in embankments with low freeboard and regular filling patterns to mitigate vulnerability and security risks. Reinforced cutoff wall

technology is practiced by construction projects requiring excavations in tight spaces and skyscraper construction in downtown areas to stabilize foundations. Apparently reinforced concrete footings are installed at construction sites in close-space situations to provide work areas. The steel reinforcement panels are fabricated and placed in a trench which is back filled with concrete. This technology is being considered in high risk Reclamation embankments to mitigate security concerns.

In the embankment security mitigation scenario, a reinforcement steel panel is installed in a bentonite slurry stabilized trench previously excavated from an embankment. When the steel panels are properly positioned, the slurry supporting the trench walls is displaced by a concrete mixture which hardens and forms a shallow reinforced concrete diaphragm. There appear to be potential materials and corrosion problems associated with reinforcement steel embedded in concrete installed in bentonite slurry. Problems include the bond of the hardened concrete to slurry-clay coated steel, continuity of the concrete placement, the ability of the clay-coated steel embedded in hardened concrete to resist corrosion, and potential deflections of a stiff cutoff wall by increased pressure and gradients.

Dam safety issues will occur as our embankments age and reveal foundation problems associated with seepage. Potential foundation seepage issues include carbonate foundation seepage around dissolutioned joints, in situ pervious overburden materials, rock joint erosion due to increased hydraulic pressure and gradient, erodible soils, and erosion of embankments due to rapid dewatering and drawdown.

Signatures

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The report benefited from a discussion with Mark Bliss, 86-68313, and a final review by Jeff Farrar, 86-68320.

Appendices

A. Case Histories
B. Literature Search

Appendix A - Case History of Cutoff Wall Applications

Fontenelle Dam

Fontenelle Dam is located on the upper Green River, north of Green River Wyoming.

The near failure of the embankment in September 1965 is documented in the 2009 CFR and its references. A continuous seepage barrier parallel to the embankment dam axis was installed from 1985 to 1987.

Fontenelle Dam in founded on sedimentary rocks of the Green River Formation consisting of thinly bedded calcareous sandstones, siltstones, shales, and minor beds of limestone. Individual beds range from less than a foot to several tens of feet in thickness. Bedding dips at very low angles (one to 2 degrees) downstream and from the right toward the left abutment. The soluble minerals gypsum, thenardite and analcite are reported in drill hole core logs above the groundwater in both abutments. These minerals occur primarily as fracture fillings and coatings on open joints and in bedding plane layers. Travertine deposits were encountered in a number of drill holes in the left abutment between approximate elevations 6404 and 6415.

Three main discontinuity sets have been measured and described at the site:
1) bedding plane joints, 2) vertical to near vertical tectonic joints, and 3) near vertical relief jointing predominantly within the massive sandstone units. The bedding plane joints are evident within the platy siltstone and fissile shale units. The near vertical relief jointing occurs predominantly within the massive sandstone units and within an area bordering the steep abutments. Deep open joints roughly parallel the abutment and extend at least to the bottom of the sandstone units. Five of these open joints were encountered in the spillway inlet excavation, and one was exposed in the spillway chute. They attain an open width of up to one foot and are generally vertical and roughly parallel to the abutment contours.

A continuous seepage barrier parallel to the embankment dam axis was installed from 1985 to 1989 due to piping deficiencies and apparent incompetent foundation rock. The seepage barrier is composed of a 2 foot thick concrete wall designed to penetrate the embankment Zone 1 material and foundation rock. The Comprehensive Facility Review (CFR) indicates the cutoff wall penetrates the foundation to about a 20 foot depth. The CFR purpose of the cutoff wall is to reduce piping of the embankment but Rice (2007) indicates it also improved fractured portions of the foundation in contact with the embankment.

Eight foot long concrete panels were installed in the embankment with a rock-mill-type excavator and bentonite slurry to prevent collapse of the trench walls. The trench was subsequently backfilled with Micro fine cement and Portland cement concrete. Secondary panels were excavated at the primary panel contacts and

backfilled with concrete to ensure continuity of the barrier. The river outlet works (ROW) area was grouted where embankment excavation and placement of concrete was restricted by the existing ROW structure. There is evidence of defective joints in the cutoff wall.

Rice, 2007, indicates short term performance of the seepage barrier is good. The seepage barrier appears to be effectively reducing flow in the embankment, except for evidence of leaks in the embankment at panel joints. Longer term, the results are mixed according to Rice. Evidence indicates decline of seepage resistance due to defects in the cutoff wall joints and fractured and weathered foundation rock in contact with the embankment.

Small deformations in the cutoff wall have been documented by Rice 2007 with the extensive monitoring system in place but do not appear to be causing excessive seepage. The deformation analysis was performed on a cross section of the barrier near the center of the dam where the barrier is full depth. He observed a bow shaped deformation pattern. The bow shape likely indicates tensile strengths sufficient to crack the concrete barrier.

Navajo Dam

The 2009 CFR indicates that wet spots developed on the downstream portion of the embankment after construction and reservoir filling with significant water collecting at the left groin. The potential for failure was significant and justified the installation of a seepage barrier on the left abutment and a seepage collection system on the right abutment.

Navajo Dam and Reservoir is located in the broad, structurally horizontal San Juan Basin in NW New Mexico. The Tertiary San Jose Formation underlies and crops out in the area of the dam and reservoir. It is primarily massive fine- to medium-grained sandstone with shale and siltstone lenses that are 1 to 20 feet thick and have horizontal extents of generally less than 400 feet.

Surficial deposits found at the site consist of alluvium, colluvium and terrace deposits. The colluvium covers the slopes of the canyon and is composed of large boulders, cobbles, gravel, and sand. Terrace deposits are well graded to silty gravels with quartzite cobbles and boulders. The alluvium is composed of unconsolidated gravel, sand, and silt.

The San Jose Formation underlies the dam and reservoir. The ancient alluvial deposit primarily consists of relatively flat-lying, massive sandstone. The sandstone is interbedded with shale and siltstone lenses. The sandstone forming the vertical bluffs in the area is massive and moderately to weakly cemented. Localized zones of sandstone can be weakly cemented to uncemented and potentially erodible. Cementing agents in the sandstone are silica, calcite and gypsum. Gypsum occurs as thin joint fillings and as secondary intergranular cement.

Near-vertical stress relief joints, along with regional and bedding plane joints, were noted in both the left and right abutments, requiring near-surface blanket grouting in the left abutment. The near vertical stress relief joints are very continuous in the upstream-downstream direction. Large grout takes during construction were thought to be due to the stress relief joints.

During construction, it was discovered that the joint system on the left abutment was much more extensive than originally anticipated. This jointing condition appeared to extend at least 50 feet into the abutment. Some of the rock was removed in an attempt to reach unjointed rock but it was apparent that if all fractured rock were removed there would be a great increase in the amount of excavation necessary. Rock was removed until the face appeared firm. The joints were then sealed by blanket grouting.

About 19 and 7 foot wide concrete panels were installed in the embankment with a rock-mill-type excavator and bentonite slurry to prevent collapse of the trench walls. The 40-inch thick concrete diaphragm wall penetrated into the left abutment about

110 feet and parallel to the dam axis to reduce erosion of the embankment material at the foundation embankment contact. The wall is about 436 feet long and penetrates up to 180 feet into the foundation rock. The installation of the wall rerouted flow from the embankment and likely deeper into the foundation.

The 2009 CRF indicates the accuracy of the piezometer data in the left (and right) abutment is highly questionable. The current instrumentation system is providing poor quality data and is very difficult to interpret when assessing failure modes at Navajo Dam. According to the CFR, the performance of the seepage barrier is unknown due to poor performance of the piezometer network. Also, large slurry losses were documented at the foundation embankment contact during construction according to the 2009 CFR Evaluation of Design, Construction, and Analysis. Slurry losses were stopped after 120 cubic yards of sand and gravel were dumped into the excavation during panel 33 installation.

Rice, 2007, indicates the seepage barrier on the left abutment reduced flows through the embankment immediately after construction and increased the seepage path through the foundation effectively reducing seepage at the foundation embankment contact. Longer term, it appears that flows are increasing with the potential effectiveness of the seepage barrier system decreasing. Rice, 2007, discusses a paper by Davidson, 1990, indicating cracks documented in the concrete cutoff wall that align with foundation cracks are due to strain and subsequent stress cracking.

Virginia Smith Dam (Calamas)

Seepage analysis of the pre-construction foundation indicated uncontrolled and excessive flows could cause piping in the foundation and heaving in the embankment toe. The seepage barrier installed during construction appears effective in reducing seepage.

Virginia Smith Dam (originally Calamus Dam) is located in the southeastern portion of the sand hills region, an area of stabilized sand hills covering more than 20,000 square miles of north-central Nebraska.

The dam is located in sand dunes that trend southeast-northwest in a shallow valley cut by the Calamus River. Both abutments are constructed in sand dune deposits from about Sta. 69+50 to 29+00. The valley section of the dam is founded on recent alluvial and glacial fluvial deposits.

The ground surface is a rolling plain of windblown sand, sand dunes, and interdune depressions. Regional bedrock is the Ogallala Formation, which is a thick section of continental deposits. The Ogallala Formation is not exposed at the dam but crops out in several locations along the North River. In the vicinity of the dam the Ogallala Formation consists of fine, silty and clayey sands to poorly indurated sandstone. Pleistocene age fluvial sand and windblown loess deposits overlie the Ogallala Formation at the dam site.

Investigations for design and construction subdivided the deposits into eight units, seven of which are surficial and one bedrock unit of the Ogallala Formation. With the exception of the river outlet works stilling basin the dam and other structures are founded in the surficial deposits.

Virginia Smith Dam was designed with features to minimize seepage including a trench, upstream blanket, slurry wall, relief wells, and toe drains. Seepage analysis of the pre-construction foundation indicated uncontrolled and excessive flows could cause piping in the foundation and heaving in the embankment toe.

The CFR indicates that a soil-bentonite cutoff wall was installed about 300 feet upstream of the embankment centerline. The seepage barrier was designed to control seepage through the foundation and was installed during construction of the embankment to improve the foundation. The seepage barrier extends into the Ogallala Formation on the right abutment and about 45 feet deep into soft sediments and fine- and silty-sand on the left abutment. The foundation trench is up to 50 feet deep with an average depth of about 20 feet.

Rice 2007 indicated that the seepage barrier reduces the seepage beneath the dam and intercepts any high permeability channels in the foundation rock. The wall widths were constructed to limit blowout of the barrier. Relief wells reduce the hydraulic

gradients and uplift pressure beneath the dam. The seepage barrier appears effective in reducing the hydraulic head across the barrier and overall performance of the seepage barrier system is stable.

New Waddell Dam

New Waddell Dam is located on the Agua Fria River about 35 miles above the Gila River confluence.

Seepage barriers were constructed during early construction in two locations of the embankment alignment. The seepage barriers were located in deep alluvial channel structures that were difficult to dewater and excavate. The barriers penetrate bedrock about 10 feet.

Regional topography is comprised of mesas and ragged to rounded hills separated by deep alluvium-filled basins. Geology at the dam site is complex, characterized by thin alluvial soils and a conglomerate unit overlying interlayered volcanic units. Portions of these rocks have been eroded, brecciated and faulted

Faulting at the site is believed to be inactive as faults are only observed in Tertiary volcanic units. Joint/fracture characteristics vary widely among the bedrock units and among locations across the dam foundation. The orientations of bedrock jointing at the site is essentially random, especially in the volcanic units.

No quantitative seepage analysis was performed prior to construction. The seepage barrier was installed in response to foundation conditions and dewatering issues in channel structures during construction. Two cutoff walls were constructed through older alluvium to rock within the center channel along the dam centerline.

Several narrow and locally deep alluvium-filled buried channels occur within the footprint of the dam. A variety of designs and construction methods were used to provide positive seepage-cutoff through the alluvium in these channels. The most significant of these channels crosses the dam foundation area from the right abutment upstream toe through the hill on the left abutment downstream toe. Additional, north-south trending buried channels cross the middle and lower portion of the right abutment foundation.

The barriers were excavated in 20-foot sections with conventional excavation equipment and bentonite slurry to prevent collapse of the excavation walls. Concrete panels were placed with conventional concrete through tremie pipes. The joints between panels were grouted.

The seepage barriers appear to improve the foundation and control most seepage.

Meeks Cabin Dam

Seepage in the downstream left abutment and downstream natural springs were observed at first filling. Flows correlated with reservoir levels and seepage control with drains was not successful. Increased flows and sinkhole formation indicated movement of materials. A cutoff wall penetrates the dam and impervious glacial tills to 170 feet in depth.

Meeks Cabin Dam is located on the north side of the Uinta Mountains in Wyoming. Meeks Cabin Dam occupies the site of a terminal moraine of the youngest glacial event during the Pleistocene epoch in the Uinta Mountains. The dam was constructed in a valley eroded into the moraine by the Blacks Fork River.

The stratigraphy at the damsite consists of Quaternary alluvium, several Quaternary glacial deposits and one bedrock unit. The glacial deposits are divided into three distinct till units (Qt_1, Qt_2, and Qt_3) and two pervious outwash gravels (Qg_1 and Qg_2). The till units are mostly impervious and the outwash gravels are generally pervious.

The Tertiary age Bridger Shale bedrock unit is not exposed in the dam foundation or in the reservoir area but was encountered in drill borings and within the outlet works stilling basin excavation. The formation is shale and siltstone with large quantities of gypsum. In places the shale is bentonitic and highly plastic and soil tests show high liquid limit clays and silts (CL and MH-CH). The shale is soft and weathered in the upper part and it exhibits low permeability. This formation was not involved in the dam safety modification cutoff wall construction but was exposed in the outlet works stilling basin excavation and likely responsible for foundation movements during construction.

A deep cutoff wall of backfilled impervious Zone 1 material was originally intended to provide cutoff to the Bridger Shale in the valley section and tight impermeable glacial till. The design grade for the cutoff was not reached during construction and the cutoff wall was founded on mostly permeable gravels and sands on the left abutment at about 46 feet depth. Also, a cutoff trench in the left abutment did not completely penetrate pervious and impervious till materials.

Exploration for the design of the cutoff wall was accomplished in 1991. Three exploratory trenches at the toe of the dam and five exploratory holes were completed from the crest of the dam on the left abutment to supplement information gathered in previous explorations. Two additional holes were drilled in 1992 near the ends of the proposed cutoff wall to determine the limits of the cutoff wall modification. Drilling was conducted by a Contractor during the 1995 cutoff wall modification to ensure that the low-strength concrete panels were completed through the pervious Outwash Gravel (Qg_l).

Investigation of the foundation glacial tills and outwash showed that the foundation contained pervious open-work granular materials which allowed significant seepage and movement of material. The Dam Safety Modification mitigated unacceptable risk of failure due to seepage and foundation stability issues. The design grade for the cutoff was not reached during construction due to large boulders and the cutoff wall was founded on mostly permeable gravels and sands on the left abutment at about 46 feet depth. Also, a cutoff trench in the left abutment did not completely penetrate pervious and impervious till materials.

A 3-foot thick wall was installed to cut off the seepage through pervious tills. The trench was excavated 10 feet into mostly impervious glacial till using conventional construction equipment and a rock-mill-type excavator and bentonite slurry to prevent collapse of the trench walls. The trench was supported with a bentonite slurry and tremie-backfilled to form separate low-strength concrete panels and subsequent excavation of embankment and panel-edge materials and backfilling with plastic concrete to form a tight, continuous wall.

The wall is 825 foot long and extends from the left abutment to left of the spillway near the center of the dam. The wall penetrates the impervious glacial tills from 130 to 170 feet in depth. The wall was constructed of a plastic concrete using low-strength concrete which matches the deformation properties of the embankment materials. The low strength plastic concrete wall appears resistant to cracking, intact, somewhat flexible

Post-construction seepage and stability conditions in the left abutment area are greatly improved and the performance of the cutoff wall is considered satisfactory.

Jackson Lake Dam

The original hydraulic fill embankment and upper parts of the foundation were susceptible to liquefaction and required stabilization. A cutoff wall was installed during major modifications to Jackson Lake Dam.

Jackson Lake Dam is located in northwestern Wyoming. The most conspicuous geologic feature at the site is the Teton Mountain Range west of the dam and reservoir.
From late Pliocene to recent time, sediment eroded from the uplifted mountains and accumulated in the basin. Additionally, large volcanic eruptions blanketed the region with deposits of ash and welded tuff.

Jackson Lake Dam is located on one edge of a deep glacial scour trough in the Jackson Hole Basin. Terminal moraines produced numerous glacial lakes at valley mouths along the Teton Mountain Range toe. In the last glacial period, a moraine backed up the Snake River, forming a natural lake (ancestral Jackson Lake). Jackson Lake Dam was constructed at the outlet of this lake. Dam construction raised the natural lake water level about 35 feet.

The left (north) embankment of the dam and majority of the embankment is founded on unconsolidated fluviolacustrine deposits (Qf). Unconsolidated material depths range from about 35 feet at the south to more than 600 feet at the north embankment end. The stratigraphy of the fluviolacustrine deposits are complex and vary along the alignment.

The Huckleberry Ridge Tuff (Qh) is a slightly to moderately weathered, porphyritic welded ash flow tuff. A zone within the Huckleberry Ridge Tuff, between 22 and 35 feet beneath the top of the welded tuff is a less competent, nonwelded volcanic ash layer subunit. This ash layer has low cohesive and frictional strength and is moderately deformable. The ash ranges from 5 to about 10 feet thick and is soft, and crumbly. The Huckleberry Ridge Tuff and ash is underlain by older glacial drift (Tg) at depth.

The deepest geologic unit encountered for the structure foundations, the Pliocene-Pleistocene glacial Till (QTg), is the only unit that underlies the entire dam. The till consists of sand, gravel, cobbles, and boulders to 18 inches, in a light tan silt matrix.

A cutoff wall was installed during major modifications to Jackson Lake Dam during the late 1980's to address potential liquefaction issues of the north embankment foundation materials. The details of the two-stage modifications are documented in the 2010 CFR Evaluation of Design, Analysis, and Construction pages 4 to 12 and 16 to 23.

The modification of the north embankment foundation involved stabilization procedures including dynamic compaction of the foundation, construction of soil cement walls beneath the upstream and downstream embankment foundation, and construction of an upstream cutoff wall, with reconstruction of a zoned, rolled, earth fill embankment. A cutoff wall was placed upstream and founded on bedrock to reduce the likelihood of seepage. The CRF figure 4 illustrates the location of the cutoff wall.

The foundation was improved with densification using deep dynamic compaction and deep-mixed soil-cement columns arranged in a honeycomb pattern to create a about 50-foot wide buttresses under the upstream and downstream embankment toes. A 4000 foot long soil-cement seepage barrier was constructed with a two-foot thick, deep soil-cement wall upstream of the embankment. Rice indicates the seepage barrier is tied into a low permeability blanket on the embankment to impede seepage flow.

The seepage barrier was constructed using deep soil mixing techniques resulting in about a 2-foot wide continuous wall. Primary and secondary borings were installed before the soil-cement hardened to create a continuous wall of soil cement. The soil-cement compressive strength ranged from 400 to 800 lb/in^2.

Seepage volumes measured since 1989 indicate satisfactory seepage control performance of the cutoff wall embankment system.

Twin Buttes Dam

Since initial filling of the reservoir in 1964, the central portion of the dam was prone to foundation seepage. During construction of the dam, borrow areas excavation exposed an alluvial gravel layer beneath the dam and downstream of the embankment. Also, a portion of the upstream equalizing channel between the Middle Concho Pool and the South Concho Pool penetrated the surficial clay layer and exposed alluvial gravel layer to the reservoir. The exposure of the alluvial gravels to the reservoir led to significant seepage underneath the dam embankment. Seepage during major flood events increased the potential for embankment instability and/or the initiation of internal erosion of the foundation. A soil-cement-bentonite (SCB) wall and a cutoff trench were installed.

Twin Buttes Dam is located just upstream of the City of San Angelo, Texas. Construction of the dam was completed in 1963. The dam is a homogeneous rolled earthfill embankment.

Seepage was first noted in the downstream left bank of the South Concho River in 1964, just one year after the completion of the 8.2 mile long Twin Buttes Dam. In August 1971, major inflow to the reservoir caused the Middle and South Concho pools to rise to elevation 1927, after which seepage appeared at the downstream toe between Stations 278+00 and 299+00 (2,100 linear feet) and extended about 1,500 feet downstream. In October 1974, another major inflow caused the reservoir to rise to elevation 1941 and the downstream seepage area expanded substantially, totaling about 10,000 feet along the embankment toe, centered between dam Stations 150+00 and 275+00. This seepage reportedly extended between 1,500 and 4,000 feet downstream of the embankment toe. A system of surface drainage ditches located between the dam and the airport was constructed by the City of San Angelo in 1974 in response to the excessive seepage flows.

Since initial filling of the reservoir in 1964, the central portion of the dam (between approximate dam Station 90+00 to 280+00) was prone to foundation seepage. During construction of the dam, earthfill borrow areas were excavated within 150 feet of the upstream toe of the dam, directly exposing an alluvial gravel layer that extends downstream beneath the dam embankment between dam Stations 90+00 to 160+00 and 240+00 to 280+00. Also, a portion of the upstream equalizing channel between the Middle Concho Pool and the South Concho Pool penetrated the surficial clay layer and exposed the alluvial gravel layer to the reservoir. The combination of the lack of a continuous cutoff trench beneath the embankment and the exposure of the alluvial gravels to the reservoir led to significant seepage underneath the dam embankment. Seepage through the foundation increases significantly during major flood events when the reservoir becomes elevated, and increases the potential for embankment instability and/or initiation of internal erosion of foundation materials at the downstream toe of the embankment.

The dam foundation consists mostly of clay and calcite and highly variable cemented gravel, calcite, and sand with bedrock at each abutment. The gravel and cobbles in the alluvial deposits are predominantly limestone with some chert. Many of these alluvial deposits have been cemented to various degrees by calcium carbonate. Overlying the alluvial gravels are more recent eolian deposits consisting of mostly lean clay, variably cemented with calcium carbonate, and with local thin calcium carbonate layers. Underlying the gravelly alluvium, marine limestone, shale, marl and sandstone, and shale extend to an estimated depth of 9,000 feet overly basement granitic rocks. The bedrock is relatively flat lying.

During original construction, cutoff trenches into bedrock were constructed across the South Concho River form approximate Station 68+40 to 94+10, and across Spring Creek and the Middle Concho River from approximated Station 282+00 to 375+00. The extent of the cutoff trenches was limited to those areas where the excavation was not excessive and the clay caliche unit was of 'sufficient depth' to restrict vertical percolation into the underlying gravel unit. The bottom width of the cutoff trench varied from 20 feet to a maximum of 100 feet across the active stream channels.

The original cutoff trench was excavated into mostly shale bedrock from the left abutment and seepage has not been a problem in this area. Toward the right abutment, the cutoff trench extended into sandstone and shale bedrock.

In response to the underseepage problem, Reclamation performed remedial foundation grouting between 1976 and 1980, using drill holes through the embankment. The grouting program was terminated before it was fully completed. The grouting beneath the dam embankment did not sufficiently reduce the downstream piezometric pressures.

Reclamation installed relief wells and sub-drain systems in two downstream areas in 1982-84. Piezometric levels downstream of the dam indicated pressures were still high and that high uplift pressures could occur, potentially causing blowout and piping of foundation materials at reservoir levels as low as elevation 1940 to 1945, which is about 5 to 10 feet above the top of active conservation. It was estimated that the capacity of the existing relief well systems would be exceeded at a reservoir water surface above elevation 1945.

During the early to mid-1990s, detailed seepage and remedial design studies by Reclamation and Harza resulted in the design and construction of a soil-cement-bentonite (SCB) wall and a cutoff trench. From 1996 to 1999, an about 4.5 mile long SCB cutoff wall was constructed from dam Station 88+20 to 281+40, including "tie-in walls" at both ends along the upstream toe of the dam. The SCB cutoff wall is up to 100 feet deep and is keyed a minimum of 2.5 feet into impervious bedrock and the cutoff trench was mostly constructed on bedrock except between about stations 43+00 and 47+00. At the same time, a 2,455-foot-long clay-filled cutoff trench was constructed from dam Station 42+80 to 67+35 on the upstream side of the dam's right abutment south of the South Concho River. The trench was tied into the existing

embankment cutoff trench at both ends. The cutoff trench was a conventional open-cut excavation 5 feet into bedrock and was backfilled with compacted clay. Both the SCB cutoff wall and the cutoff trench were connected to the existing Zone embankment. This connection system included the installation of a geomembrane that joined the top of the cutoff wall or the cutoff trench with the existing dam embankment Zone 1 at the upstream slope.

Twin Buttes Dam has been modified several times to control seepage through the dam foundation. Each modification sought to either substantially decrease (cut off) seepage through the un-cemented gravel unit or to collect seepage from it in a controlled manner. The supplemental grouting, relief wells, cutoff trenches and a soil-cement-bentonite (SCB) wall described below can be considered a phased approach of remedial construction and evaluation. There is now a dual system of protection, with a cutoff trench or SCB wall extending along the entire length of the gravel unit, and a properly filtered collection system downstream to control possible leakage through the foundation cutoff trench/wall system.

Since construction of the SCB cutoff wall and trench, the reservoir pool has been very low. Because of the reservoir levels it is not possible to monitor the performance of the seepage barrier. The SCB cutoff wall and the cutoff trench are believed to have resolved the foundation under-seepage problem. However, the reservoir water surface has not risen sufficiently high to have fully tested the effectiveness of the new SCB wall and the cutoff trench as of the FY11 CFR.

A. V. Watkins

The near failure of the A. V. Watkins embankment in November 2006 is documented in the 2009 CFR and its references. A cement-bentonite wall was constructed in 2008.

A.V. Watkins Dam was constructed between 1957 and 1964 on Willard Bay, an east-extending arm of Great Salt Lake in Utah. The Wasatch Front, a sharp topographic escarpment, is less than a mile from the east side of the dam and marks the western edge of the Middle Rocky Mountain province. The Great Salt Lake is a remnant of ancient Lake Bonneville, which had an elevation approximately 1,000 feet above the present lake level.

The north and west legs of A.V. Watkins Dam are founded directly on soft lacustrine Bonneville clay deposits. The majority of preconstruction subsurface investigations, testing, and analyses focused on the western and northern reaches of the dam that would be founded upon very soft lacustrine clay deposits. The east and southeast reach of dam was underlain by a predominantly sand or silty sand deposit, referred to as "the sand reach". These very soft deposits required building the dam in four stages to allow for settlement and dissipation of pore pressures to ensure static stability.

The Quaternary Bonneville Sand "hardpan" (Qbs) at the ground surface in the piping incident area and along the entire southeast reach of the dam dips toward the north and is overlain by a thickening wedge of lacustrine sediments (Qls) on both the east and south legs of the dam.

The 2002 CFR described visual observations of past examination related to seepage as follows:

> "During the 1998 Comprehensive Facility Review (CFR) examination, seepage was apparent along most of the downstream toe of the southeast section of the dam. The seepage did not appear to be threatening the integrity of the structure, however, heavy growth and vegetation made observations difficult. Seepage was also apparent on the northern embankment extending northeast from the right outlet works exit channel. During a site examination on July 31, 2001, when the reservoir was fairly low, areas of vegetation were noted but seepage was not [3]. It was also observed that very little water was flowing through the trench drain east of the outlet works, constructed as a result of Safety of Dams (SOD) recommendation 1996-SOD-A. The extent and locations of seepage observations are typical and not expected to change; however, long term monitoring of all seepage areas is very important."

The Corrective Action Alternatives Study prepared in 2008 provides a good summary of the piping incident and interim repairs, as follows:

> "On November 13, 2006, piping erosion was observed at approximately dam Sta. 639+00 by a local landowner riding a horse along the South Drain. After emergency response personnel arrived, it was also found that excessive seepage, sand boils, and erosion were occurring at the toe of the dam. The leak had advanced to a condition close to causing dam failure. Emergency action was implemented, which initially resulted in placing gravel over the sand boils at the downstream toe until the flow velocities were reduced and then placing filter sand over the gravel. A large berm of pit-run soil was then placed over the filter and gravel. Erosion, however, continued into the South Drain. A second berm was then placed at the upstream toe of the dam in an attempt to plug upstream entrance locations of the seepage. This effectively stopped the further erosion of soil into the South Drain and the failure mode from progressing any further. At the same time, an emergency drawdown of the reservoir was begun."
>
> "…The interim repair consisted of the construction of an infilled, upstream ring dike approximately 650 feet wide to isolate the damaged section of the dam; a new 700-foot-long state-of-the-art, filtered, toe drain with three inspection wells and sediment traps; and a restriction of the reservoir to a maximum elevation of 4217 feet….Immediately upon completion of the interim repair, the CAS was initiated."

Interim repairs were completed in March/April 2007. A paper by Bliss and Dinneen describes the piping incident, possible failure mechanisms, the emergency response, and interim repairs in detail. A cement-bentonite wall was constructed in 2008. Most of the work associated with placement of the excavation spoils on the downstream face of the embankment and restoration of the crest was completed in 2009.

Piping erosion was observed along the South Drain. Excessive seepage, sand boils, and erosion (piping) were occurring at the toe of the dam nearly causing dam failure.

After the piping incident of November 2006 a cement-bentonite (C-B) wall was designed to mitigate the potential for development of piping problems through the foundation. The minimum 30-inch wide C-B wall was constructed during the summer and fall of 2008 and extends from station 468+00 to 733+00. It was constructed from the crest, through the embankment, into the clay deposits that underlie the sandy materials. As a result, the C-B wall also mitigates the potential for piping through the embankment in this dam reach. The C-B wall is expected to provide practically complete seepage cutoff because it was extended a minimum of 5 feet into the impermeable clay. Minimum depths of the wall below elevation 4234 varied from 37 to 64 feet (to elevations 4197 to 4170 feet). Excavation spoils from the trench excavation were placed on the lower half of the downstream slope of the dam, and the crest was restored to elevation 4235.

It was not possible to extend the C-B wall through the South Drain Siphon, which could have left a potentially unfiltered seepage path into the South Drain at the ends

of the concrete lined channel at the inlet and outlet for the siphon. The designers accounted for this by designing a 10-foot wide by 10-foot deep filter zone in the bottom of the channel, thus filtering the seepage before it could enter the channel.

It appears that the design of the 2008/2009 dam safety modifications drastically reduced the potential for piping within the limits of the C-B cutoff wall construction.

Appendix B - Literature Search and References

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