A.V. Watkins Dam Modification: Cement-Bentonite Slurry Cutoff Wall

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A.V. WATKINS DAM MODIFICATION: CEMENT-BENTONITE SLURRY CUTOFF WALL

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ABSTRACT

A.V. Watkins Dam is an earthfill dam approximately 14.5 miles long with a structural height of 36 feet. Located just north of Ogden, Utah, the dam impounds approximately 215,000 acre feet of water and is founded on compressible lakebed sediments of the Great Salt Lake. In November of 2006, a piping incident occurred which nearly resulted in the catastrophic failure of the dam and reservoir. While constructive measures (including a drawdown of the reservoir which greatly impacted storage capacity) were immediately taken to save the dam, the Bureau of Reclamation (Reclamation) needed a permanent solution which would effectively reduce the risk of failure below the guidelines established by the Reclamation Safety of Dams Act.

Figure 1: Location map and plan view of dam, reservoir, and cut-off wall

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For most of 2007, Reclamation drill crews conducted an extensive program of forensic analysis and geotechnical exploration in the dam embankment and its foundation for several miles on either side of the incident area. In early 2008, engineers decided that the installation of a 5-mile long, 30-inch wide Cement-Bentonite (CB) cutoff wall, along with the reconstruction of the dam embankment through the incident area, would achieve risk reduction goals and allow the reservoir to be put back into full service.

A $17.4 million construction contract for the work was awarded in latter May, and on July 21, 2008, the contractor team of Geo-Solutions (New Kensington, PA) and Nordic Industries (Marysville, CA) began excavating and backfilling the 5-mile long CB wall. After making field adjustments to the CB slurry mix and cresting the learning curve, the contractors were able to continuously produce over 2 cubic yards of slurry per minute and excavate over 9,000 square feet of wall per shift. In addition to the CB wall, the project also included a bio-polymer drainage trench and a new toe drain system.

Aerial layout of the southeast portion of A.V. Watkins Dam

INTRODUCTION

A.V. Watkins Dam, located 10 miles north of Ogden, Utah, is a U-shaped, zoned earthfill structure constructed on Willard Bay of the Great Salt Lake. The dam is more than 14 miles long, and is approximately 36 feet high at its maximum section. The dam impounds an off-stream reservoir (fed by the Willard Canal) known as Willard Bay, which has a capacity of over 215,000 acre feet and a surface area of nearly 10,000 acres. Prior to construction, a drainage canal was excavated downstream and parallel to the alignment of the southern portion of the dam in order to lower the local groundwater table and facilitate construction of the dam’s embankment. Now referred to as the South Drain, this canal continues to collect local groundwater, surface runoff (from both
precipitation and irrigation), and dam seepage flows and transports them to the Great Salt Lake. The southeast portion of A.V. Watkins Dam is shown in Figure 1.

The majority of A.V. Watkins Dam is founded on lacustrine deposits of sand, silt, and clay. Because of the compressibility and low strength of these soils, construction was staged in phases (between 1957 and 1964), to allow for foundation pore pressure dissipation and consolidation. During the reservoir’s first filling in 1975, saturated soils and unstable seepage conditions were observed at the downstream toe of the dam. To mitigate this condition, a 3.5 mile long unfiltered clay-tile toe drain was installed at the downstream toe of the southern portion of the dam. Seepage collected by this drain discharges into the South Drain.

NEAR FAILURE INCIDENT

In November of 2006, A.V. Watkins Dam nearly failed as a result of piping and internal erosion of its foundation soils. After being notified by an adjacent landowner of water flowing near the downstream toe of the dam, Reclamation and Weber Basin Water Conservancy District (District) personnel responded immediately by implementing the Emergency Action Plan. Upon arriving at the site, they observed that fine grained, sandy soils from the dam’s foundation were being piped to the downstream toe of the dam and also into the South Drain near Station 639+00, also referred to as the “incident area.” Up to 200 gpm of seepage water was exiting from sand boils at the toe of the dam and subsequently flowing into sinkholes as it made its way towards the South Drain. The seepage would then re-emerge at the bank of the South Drain, where it subsequently deposited large amounts of sand into the channel.

In a heroic effort to save the dam, hundreds of cubic yards of drain rock and filter sand were hauled to the site and placed over the sand boils and sinkholes over the next 24 hours. Approximately 5,000 yards of a well-graded pit run material was also dumped on the upstream side of the dam in order to stem the flow of water into the inlets of piping channels in the dam’s foundation. When seepage flows decreased to and finally ran clear of foundation sediments, Reclamation and District engineers began the process of determining what happened as the reservoir was slowly drawn down to a safe elevation.

FORENSIC EXAMINATION

Through a series of forensic trenches excavated between the downstream toe of the dam and the south drain, as well as an extensive drilling program, Reclamation discovered that approximately 5 miles of A.V. Watkins Dam was constructed on deposits of highly erodible, poorly graded fine sand. It was subsequently determined that within this highly susceptible layer, piping, after initiating at the south drain (from seepage through the foundation), progressed upstream, underneath the embankment, and eventually reached the reservoir. With piping conduits fully penetrating the foundation, hydrostatic pressures at the toe of the dam increased, resulting in sand boils, erosion of the foundation (causing sinkholes, collapse of hardpan layer, etc.), and slope failures. The existing clay-tile toe drain was found to be plugged with sand, and therefore not able to
effectively relieve pressures at the toe. At the conclusion of this examination, Reclamation realized that any portion of the dam built on similar foundation conditions would be susceptible to the same failure mode as occurred in the November 2006 incident. Figure 3 describes the mechanics of this near failure.

![Figure 3: Dam section at incident area describing failure mode](image)

**GEOLOGY**

A.V. Watkins Dam is located immediately west of the Wasatch Range, within 1 mile of the Wasatch Fault, in the Middle Rocky Mountains province. The dam is built across, and atop, a former bay of the Great Salt Lake known as Willard Bay. Geologic mapping by the USGS characterizes the deposits in the southeastern portion of the dam as “Lacustrine Deposits consisting of gravel, sand, and clay deposited in the fluctuating waters of Lake Bonneville and the Great Salt Lake.” (Personius, 1990)

Specifically, the deposits through which the CB cutoff wall was excavated (directly under the dam) fall into three basic categories. The first layer, labeled Qsl (Quaternary shoreline deposits), consists primarily of silty sands, silts, silty clays, and clays with a high organic content. In general, these deposits overlie the Qbs deposits at the north and southwest ends of the modification and represent Holocene age (shallow, near-shore) estuary or swamp deposits.

The second layer, called Quaternary beach sand (Qbs), is typically found immediately underneath the dam for most of the length of the modification and appears to extend 20 to 33 feet deep. This layer of poorly graded sand, silty sand, and “hardpan,” was deposited in the late Pleistocene by the fluctuating or receding shoreline of Lake Bonneville. The hardpan layers, which are believed to have played a significant role in the near failure of the dam, consist of sand cemented by calcium carbonate and can be extremely difficult to excavate, requiring a hammer or a heavy steel rod to break.

Finally, the Bonneville Clay (Qbc) layer underlies the Qsl and Qbs deposits throughout the reach of the cutoff wall. The Qbc is organic and very soft, generally exhibiting zero blow counts and sinking under the weight of drill rods in SPT holes. The total thickness
of the Qbc exceeds 150 feet, the limit of original pre-dam construction borings, and may extend to depths of thousands of feet. (Pearson, 2007)

Figure 4: Geologic section of dam and foundation at Station 637+50

Figure 4 illustrates a typical geologic cross-section of the dam and foundation, showing the Qbs (including hardpan) and Qbc layers. A 5-mile portion of the dam, between Stations 468+00 and 733+00, was considered to be founded on similar geology.

INTERIM REPAIR (PHASE I)

By January 2007 (2 months after the near failure event), the reservoir had been drawn down to elevation 4214 feet, which represented a loss of over 125,000 acre feet of water storage. An interim repair, known as Phase I, was needed to improve conditions enough so as to allow increased storage in the reservoir until a long-term repair (Phase II) could be constructed.

Beginning in March 2007, Reclamation constructed (at the incident area) an upstream ring dike embankment (see Figure 2), an upstream filter sand interceptor trench, and completely replaced the existing toe drain. This new toe drain consisted of perforated HDPE pipe enveloped in drain rock and filter sand, and replaced a 700 foot long portion of the old clay-tile drain. Before outfalling into the south drain, the toe drain passed through 3 inspection wells, each equipped with sediment traps and flumes. The Phase I repair, completed in May of 2007, allowed the District to fill the reservoir to elevation 4217 (4226 represents full capacity).
CUTOFF WALL DESIGN

Using seepage models and the extensive geotechnical data collected in 2007, Reclamation’s Technical Service Center (TSC) calculated that it was necessary to limit the hydraulic gradient in the foundation soils to a maximum of 0.04 in order to prevent the piping and internal erosion activity observed in the 2006 event. A number of alternatives were considered, but only the cutoff wall alternative addressed all of the failure modes identified in the risk analysis. For example, a new toe drain at the downstream toe of the dam, constructed with modern filter criteria, did not fully address seepage into the south drain. A filter zone at the south drain would not prevent seepage from occurring at other locations downstream of the dam (which were observed in a number of places during the 2006 incident). Also, any kind of interceptor trench associated with a new toe drain would have to extend below the hardpan layer, making construction both difficult and expensive. Finally, combining an extensive filter zone and a new deep toe drain (in order to address all failure modes) would be extremely cost prohibitive given a repair length of over 5 miles.

The cutoff wall alternative, while addressing all known failure modes, allowed for several different methods of construction, all of which called for the slurry to support the sidewalls of the trench. A soil-cement-bentonite (SCB) wall was rejected because it would not only be too expensive, but it would be too strong – the wall needed to be ductile, capable of withstanding the movement associated with a floating earthen dam. Also, SCB slurry construction requires a larger staging area adjacent to the wall than does its CB counterpart. A soil-bentonite (SB) wall was also considered, but later rejected because 1) the narrow crest of the dam did not allow for an appropriately sized mixing area, and 2) soil bentonite’s inherent lack of resistance to internal erosion. A cement-bentonite (CB) wall, on the other hand, appeared to capture the advantages of both methods. The cured CB material would provide some strength, resisting internal erosion, yet also be ductile enough to flex with the embankment. The CB construction process would require no working platform on the dam crest, and the slurry itself would have the
ability to fill voids and existing defects (encountered in the walls of the trench) in the embankment and foundation. Once inside the voids, the CB slurry would cure and become immovable. According to data available throughout the industry, the cured CB (using normal Portland Cement) would have permeabilities of between $1 \times 10^{-6}$ and $1 \times 10^{-5}$ cm/sec. Finally, given all advantages and disadvantages, CB appeared to provide the most impermeable, yet ductile, cutoff for the least amount of money. In January 2008, Reclamation entered the project’s final design phase using the CB cutoff wall similar to that shown in Figure 5.

In addition to the CB cutoff wall, Reclamation also needed to repair a 300-foot long section of the dam embankment suspected of being damaged during the November 2006 near failure. In a “belt and suspenders” approach to eliminate lateral seepage along the hardpan layer (approximate elevation 4208 feet), the TSC called for the damaged portion of the dam’s embankment, as well as its downstream foundation, to be removed. The poorly graded, sandy foundation material (Qbs) between elevation 4214 and 4205 would be replaced with well-compacted material from the dam’s embankment. The dam itself was to be reconstructed using a combination of embankment material, filter sand, and a well-graded silty gravel material which would form the dam’s outer shell. A cross section of the dam through the incident area, near Station 638+00, is shown in Figure 5.

**PRODUCTION OF CEMENT BENTONITE SLURRY**

Nordic Industries and Geo-Solutions arrived on site in early July 2008 and began clearing areas along the southeastern portion of the dam adjacent to Interstate I-15. This location (Station 733+00), considered to have the geologic profile least susceptible to internal erosion, included a 2,000 foot “test section” and was to be the project’s first heading. It was Reclamation’s intention that any inconsistencies in the slurry mixing process, as well as problems inherent with trench excavation, would be ironed out prior to moving west towards the more critical areas of the project. In addition, samples of the CB slurry were to be taken daily through the test section and subsequently analyzed at both 14 and 28 days, thereby providing assurance to Reclamation that the cured CB achieved both the strength and permeability requirements called for in the specification.

When the CB plant was completely assembled, it contained a bentonite storage area, a bentonite slurry pond, one or two cement silos and guppy, a mobile Baker tank for water storage, a positive displacement pump, a large capacity generator, and a custom-built mixing plant designed by Geo-Solutions’ founder Chris Ryan. This specialized plant, consisting of a small hopper adjacent to a 5-cubic yard continuous mixing tank, was controlled by infra-red level detectors and a continuous-flow density meter. As bentonite slurry was pumped into the tank, cement from the vertical silo, as well as lignosulfonate from the small hopper, was augured into the tank in specific proportions measured electronically by the plant operator.

The CB slurry, as defined in the specifications, called for 1685 lbs (1 cubic yard) of water, 303 lbs of Portland Cement (Type V), and 101 lbs of bentonite (API 13A Section 9). Typical for the industry (PCA, 1984), this represented a mix design of approximately
6% bentonite and 18% cement by weight of water. Although not specifically identified, Reclamation also allowed for the use of viscosity modifying additives, such as lignosulfonate, in manufacturer recommended proportions.

![Image](image.jpg)

**Figure 6:** The PC1250 excavator is approaching the CB plant and staging area

Geo-Solutions and Reclamation commenced to mix trial batches of CB slurry on July 18, 2008, in order to verify that the design mix of lake water, bentonite and cement called for in the specification could be effectively produced in the field. By July 21, the contractor began excavating the CB wall using a slurry that contained between 5% and 6% bentonite and 18% cement (by weight of water), with minor amounts of lignosulfonate added per cubic yard to reduce viscosity. Because the CB slurry was mixed continuously, target units weights of 64.5 pcf for the bentonite slurry, and 71.8 pcf for the CB slurry, as well as minimum Marsh Funnel viscosities, were used to control the quality of these slurries in the field.

**CONSTRUCTING THE CB WALL**

The specification called for the contractor to begin wall construction on the far east end of the project (Station 733+00) and excavate in a southwesterly direction. In order to accomplish this, the CB plant was assembled for the first time at Station 709+00. CB slurry was then pumped (via the positive displacement pump) through a 6-inch HDPE pipeline to the trench heading nearly 2,700 feet away at a continuous rate of up to 400 gpm (approximately 2 cubic yards per minute). Over the next three weeks, the contractor worked his way around the southeastern portion of the dam (where the wall averaged about 50 feet in depth), and in the process excavated over 240,000 square feet of wall (5,100 linear feet). When they finally stopped excavating in order to move the plant to the next location, they were still pumping nearly 2 cubic yards of slurry per minute at a distance of well over 2,500 feet.
Early quality control testing from 3-inch by 6-inch cylinders, cast on a daily basis, indicated that although the cured CB lacked some compressive strength, it did achieve the project’s permeability goals. Fourteen-day cylinders cast within the first 5,000 feet of CB wall broke (on average) at 9 psi and achieved an average permeability of $6.1 \times 10^{-6}$ cm/sec.

As wall construction proceeded in a westerly direction, the contractor crested the learning curve and productivity increased. As the trench was excavated by the Komatsu PC1250, spoils were pulled out through the CB slurry and deposited on the downstream slope of the dam. Poorly graded silty and sandy soils immediately flowed to the downstream toe of the dam, while spoils from the dam’s embankment, as well as the target Qbc layer, remained higher up on the slope. This served the contractor well when it became time to construct the cap atop the cured CB wall. After excavating for approximately 2 hours, the contractor, in the presence of Reclamation’s full-time geologist, would sound the depth of the trench and verify that the excavation had penetrated at least 5 feet into the Qbc. The final depth was then marked on wooden lathe located every 20 feet along the upstream crest of the dam. When the CB plant was relocated to a new location, the contractor moved his excavator several thousand feet away and then excavated in a direction back towards the plant. The contractor found that it was easier to shorten the HDPE supply line by cutting it, rather than lengthen it by fusing on more pipe, as excavation progressed.

In mid-August, when enough cement and bentonite had been stockpiled on site, the contractor added a night shift to his CB wall excavation operation. As expected, productivity doubled. Slurry waste factors decreased because the contractor no longer had to excavate at least 5 feet back into the previous day’s work. Also, slurry pond viscosities and unit weights were easier to maintain because the pond was being continuously recirculated. During peak productivity, the contractor was able to excavate over 450 linear feet of wall and 24,000 square feet of wall per day (over 2 shifts).

![Figure 7: Photograph of typical CB wall excavation](image-url)
While both Reclamation and the contractor were pleased with these record-setting production rates, moving along at this pace did present some challenges. A constant train of cement delivery trucks was necessary to keep the 350 ton-per-day CB plant in operation. When cement or bentonite deliveries were delayed, so was excavation. When it came time to move the CB plant to a new location, cement silos and multiple palettes of bentonite and lignosulfonate had to be moved as well. Trench excavation at times outpaced slurry production, leaving some low spots in the wall. According to the specification, these low spots had to be brought up to within 6 inches of surface of the crest within 7 days. On several occasions, the contractor had to “top off” the low spots using mixer trucks and concrete pumps. High production rates can also be rough on heavy construction machinery. In order to prevent significant break-downs and constant mechanical failures, the contractor established and subsequently followed a strict lubrication and maintenance program.

While excavating through the embankment, Qbs, and Qbc layers proved to be fairly easy, the contractor did experience some difficulty getting through the hardpan. The operators of the PC1250 found that the best way to get through those lenses was to chip off small (12 to 18-inch) pieces of the hardpan from above, as opposed to prying it up from underneath, and then patiently remove the rock-like chunks from the trench as soon as possible. While some equipment failures did occur, the combination of full-time mechanics and spare parts for the excavator (and other key equipment) allowed the contractors to maintain their aggressive schedule.

Figure 8: Detail showing new cutoff wall cap and gravel driving surface

Once the CB wall had cured for at least 14 days, the contractor was allowed to come back and rehabilitate the crest of the dam, as well as the downstream slope and toe. In order to allow for future vehicular traffic, the top 18 inches of CB was removed and an earthen cap was constructed in its place, using a mixture of embankment and Qbc spoils. Six inches of compacted roadbase formed the final driving surface on the dam’s crest. Using bulldozers and excavators, the contractor used the remaining excavated material to reshape the downstream face of the dam. Finally, the topsoil, stripped off of the slope prior to excavation, was replaced on the slope and subsequently reseeded.
Although production slowed while excavating through hardpan layers, as well as around the tight radius curves in the south marina, the contractor succeeded in completing the first contract milestone on October 15, 2008. For the next 5 weeks, he made his final push to the west and by November 22, 2008 – nearly a year ahead of the contract’s milestone requirements – he completed the entire CB wall.

EMBANKMENT RECONSTRUCTION IN INCIDENT AREA

Figure 9: Photograph of embankment reconstruction in incident area

Given the high groundwater table in the project area, the contractor was required to install, and then pump continuously from, a filter sand bio-polymer trench (see Figure 4) prior to excavating out the incident area. In addition, the CB wall through the incident area was to be completed a full 28 days prior to any work at this location. Constrained by these two events, the contractor did not begin work in the incident area until October 6, 2008. Excavation operations proceeded until the contractor reached elevation 4208, approximately 3 feet above the target elevation and immediately below the hardpan layer. For the next 10 days, they worked to dewater the flowing, silty Qbs to the point where they finally reached the required excavation at 4205. After Reclamation inspected, and then accepted the foundation of the excavation, the contractor commenced to reconstruct the dam as quickly as possible. Although backfill operations were severely hampered by several weeks of extremely wet weather, the contractor was able to complete all earthwork at the incident area, including the new toe drain, by the contract milestone date of November 21. Figure 9 shows the zoned dam embankment being reconstructed in the incident area.
CONCLUSION

In completing the 5 ½ mile long CB wall on-schedule and within budget (no claims), the contractor team of Geo-Solutions and Nordic Industries efficiently balanced CB slurry production (and associated cement and bentonite supplies), the plant’s distance from the excavator, and the rate of excavation. CB slurry was pumped, on average, over 2,600 feet from the plant to each new heading, with occasional distances of nearly 3,000 feet. When the excavator was more than 2,500 feet from the plant, it became more difficult to pump the CB slurry through the HDPE supply line and flow rates often decreased. As the excavator drew nearer to the plant, the flow of CB increased, and the excavator was hard pressed to keep ahead of slurry production.

Although minor setbacks hindered slurry production from time to time, the contractor skillfully maintained a consistent bentonite slurry pond and subsequently produced a consistent CB slurry. Unit weights and viscosities were monitored continuously by the contractor and verified every 2 hours by Reclamation. The end result of these efforts was the successful production of over 175,000 cubic yards of CB slurry, which, upon curing, provided the cutoff wall with an average permeability of 5.8 x 10^{-6} cm/sec (28 day).

Of greatest significance, perhaps, is that the contractor team of Geo-Solutions and Nordic Industries were able to install over 40,000 linear feet of silt fencing, excavate over 180,000 cubic yards of earth, place and compact nearly 50,000 yards of earth materials and install nearly 1.6 million square feet of CB wall in less than 5 months. As a result, the Weber Basin Water Conservancy District was able to begin storing water behind A.V. Watkins Dam a year earlier, and thereby provide an adequate water supply for the Wasatch front between Salt Lake City and Brigham City.

REFERENCES

