Tailing Storage at the Fort Knox Mine – An Innovative Expansion to Continue a History of Success

Thomas F. Kerr, P.E.
President, Knight Piésold and Co., Denver, USA

Peter D. Duryea, Ph.D., P.E.
Senior Project Manager, Knight Piésold and Co., Denver, USA

David T. Quandt
Chief Mine Engineer, Fairbanks Gold Mining, Inc., Fairbanks, USA

Abstract

Fairbanks Gold Mining, Inc. (FGMI) owns and operates the Fort Knox gold mine and mill, which has been in production since 1996. Tailing are stored behind a cross valley dam. In the summer of 2006, the tailings storage facility (TSF) dam was raised to its originally designed final crest elevation. However, in January 2009, the mill ore reserve was increased above the remaining capacity of the TSF. A site wide optimization study identified a 52-foot raise to the TSF dam as the preferred alternative for expanded capacity, but this posed a challenge. How would the raise be configured to maintain the necessary level of stability and security for the TSF given its hazard consequence classification and other site specific conditions without adopting a conventional downstream raise? The solution was to construct the 52-foot raise with partial placement of the upstream random fill shell over tailings in lieu of a downstream raise as had been the practice through 2006. The 52-foot raise then bears largely on engineered fill on the crest and upstream face of the existing dam with a modest construction onto the tailings deposited immediately to the upstream. This paper presents the design of the 52-foot raise to the Fort Knox TSF together with construction and operational experiences to date, which represents another chapter in the success of the facility.

Introduction

Fairbanks Gold Mining, Inc. (FGMI) owns and operates the Fort Knox gold mine and mill approximately 30 kilometers northeast of Fairbanks, Alaska. The mill generates tailings at a rate of approximately 39,500 dry tons per day from a carbon-in-pulp process and has been operating since 1996. Tailings are stored behind a cross valley, zoned earth- and rock-fill dam just below, and to the east of, the mill. In the summer of 2006, the tailings storage facility (TSF) dam was raised to its originally designed final crest elevation of 1488 feet above mean sea level (fmsl) making its maximum height 308 feet. However, in January 2009, the mill ore reserve at the mine was increased above the remaining capacity of the TSF, and additional storage capacity was sought. A site wide optimization study identified a 52-foot raise to the TSF dam as the preferred alternative when compared to developing a new site, but this posed a challenge. How would the raise be configured to maintain the necessary level of stability and security for the TSF given its hazard consequence classification and other site specific conditions without adopting a conventional downstream raise? Such a downstream raise would have required a new zone of fill to be constructed from the existing downstream toe of the dam all the way to the raised crest. In addition to the considerable expense and extended duration required by this type of expansion, such construction would require overcoming very difficult access conditions and relocation of an extensive seepage collection system at the existing downstream toe.

The solution was to construct the 52-foot raise with partial placement of the upstream random fill shell over tailings in lieu of a downstream raise as had been the practice through 2006. The 52-foot raise
then bears largely on engineered fill on the crest and upstream face of the existing dam with a modest construction onto the tailings deposited immediately to the upstream. Notwithstanding its partial placement on tailings, the 52-foot raise was designed to maintain its overall stability and integrity even in the event of a loss of strength due to liquefaction of the tailings. This was achieved by constructing a base platform fill of coarse rock-fill through the supernatant pond and into the underlying tailings against the original dam by locally failing the tailings and displacing the rock-fill as far downward as possible. The base platform fill was constructed in the summer of 2009 using a specification that limited the equipment to certain traffic patterns. Upon completion, the base platform fill was left in place for approximately 8 months to dissipate the majority of excess pore pressures and take up the majority of settlement in the tailings before the first stage of the 52-foot raise was built. The first stage was constructed in the summer of 2010 and involved an extensive excavation into the upstream side of the dam above the base platform fill to re-configure the seal, filter, and transition zones. Following construction of the first stage, tailings deposition was initiated from the south abutment of the dam to begin development of a drained beach against the raise, and in the summer of 2011, spigot deposition will be continued from the entire upstream crest to extend the beach. The second stage of the 52-foot raise will be constructed concurrent with development of the beach in 2011, and the final stage of the raise will be built in 2013.

Background and General Arrangement of the Tailings Storage Facility

A plan view of the Fort Knox site is shown on Figure 1. The TSF is on the left (west) side and is upstream of the water storage reservoir (WSR) on the right (east) side. The TSF is a valley type impoundment and is sub-divided into a north area that is contained behind the dam and a south area that is contained behind the Pearl Creek causeway. The causeway is a west to east rock-fill haul road that has been raised continuously from the bottom of the valley to provide construction and operator access from the mine and mill area to the dam. The TSF is unlined, but seepage is contained by groundwater that is mounded above the ultimate tailings level in the adjacent ridges and by the pit which acts as a local sink to the west. The only exit window for seepage is around the dam where the groundwater regime is locally drawn down to the valley floor, and in this area, containment is provided by a row of interception wells installed across the valley to form a hydraulic barrier just below the downstream toe.

The TSF is underlain by Fairbanks Schist, which consists of a combination of moderately hard micaceous quartz and muscovite quartz schist at higher elevations and softer graphic schist and metavolcanics with some metasedimentary rocks lower down. Fracturing is extensive, and local faults cross cut the site with both sets of features generally steeply dipping and trending southwest to northeast. Many of these discontinuities are open and unhealed beneath the dam and were incorporated into the TSF design as an under-drain for the dam and tailings deposit. Drainage is allowed to pass under the dam and is recovered by the wells described above.

The TSF dam is a cross valley, zoned, earth- and rock-fill structure that has been developed from competent mine waste sourced from zones of hard granitic intrusive rocks in the pit and from selected, heavily weathered schist and granitic materials around the site. It is currently the highest dam in Alaska and has been built in several stages following rigorous specifications for foundation preparation and fill placement. When it reached its originally designed final arrangement in 2006, the dam followed a conventional downstream approach to form the trapezoidal cross section shown on Figure 2. This section included a series of sloping zones on the upstream side, comprising of an upstream erosion protection rock-fill layer, an upstream sand filter, a low permeability seal zone, a downstream sand filter, and a transition zone; all supported on a large downstream rock-fill shell. The top of each zone was built to elevation 1488 fmsl at each abutment and 1491 fmsl in the center of the valley to
provide a 3-foot camber for settlement. An additional 6 feet of rock-fill was placed over the top of the earth-fill zones for frost protection. The crest width of the dam below the frost protection is 57.5 feet, and the upstream slope is 2.78:1 (horizontal to vertical) steepening to 2.25:1 below elevation 1443 fmsl while the downstream slope is 1.80:1.

Tailings were deposited into the TSF by gravity from a few single point pipe outlets on the west side of the northern half of the TSF, remote from the dam, and from one point on the west side of the southern half of the TSF. Single point discharges were adopted for simplicity and to reduce the potential for ice accumulation in the tailings deposit during winter. The result was that the beach in the northern half of the TSF sloped towards the dam with the soft, finer-grained tailings located against the dam under the supernatant pond.

This arrangement has provided secure, cost effective, and simple to operate tailings storage at Fort Knox for over 15 years. However, the increasing price of gold has increased the ore reserve, and there is now a need to add more tailings storage capacity at the site. The preferred alternative was found to be another raise to the dam but without a continuation of the downstream approach, which would have required a new zone of fill to be brought up from the downstream toe of the dam at considerable expense (in terms of dollars and time) and that would require relocation of the seepage collection system at the downstream toe. The solution was to construct a 52-foot raise largely on engineered fill on the crest and upstream face of the existing dam but with a modest construction onto the tailings deposit immediately to the upstream. Notwithstanding its partial placement on tailings, the raise was designed to maintain the necessary high level of overall stability and integrity required by Knight Piésold and Co. (the engineer), FGMI (the owner), and the Alaska Department of Natural Resources (ADNR) Dam Safety Program (the dam safety regulator) even in the event of a loss of strength due to liquefaction of the tailings.
Hazard Classification Rating and Design Flood and Seismic Criteria

The ADNR has established three hazard classifications of dams, which are Class I (high), Class II (significant) and Class III (low). The Fort Knox TSF dam is designed to meet or exceed the Class I (high) requirements for storm water containment and earthquake loading, which are:

- **Inflow Design Flood and Storm Water Management** – Accommodation of the probable maximum flood (PMF)
- **Maximum Design Earthquake** – Ability to safely withstand an event between the 2,500 year return period earthquake and the maximum credible earthquake (MCE)

The design criteria being followed are:

- **Inflow Design Flood and Storm Water Management** – contain the 100-year 24-hour rain-on-snow event above the maximum operations pond (6,600 acre-feet) with 3.0 feet of freeboard maintained above and retain the PMF with encroachment into the 3.0 feet of freeboard but not overtopping of the dam. The 100-year event was calculated to produce 1,546 acre-feet of runoff while the PMF was calculated to produce 3,619 acre-feet (both including for runoff into the Walter Creek heap leach pad just upstream of the TSF that, for the purposes of the TSF design, was assumed to fail and deliver these volumes into the TSF).

- **Design Earthquake** – withstand the MCE without a loss of containment in the TSF and without a loss of overall stability and integrity of the dam, although some movement and possible shallow localized slips on the upstream face of the 52-foot raise would be tolerated. An updated seismic hazard assessment indicated that the MCE comprises a shallow crustal event (strike-slip) of magnitude $M = 7-1/2$ at an assumed distance of 3 miles from the site producing a peak horizontal ground acceleration of 0.63g. Despite the fact that there are several seismogenic sources in Alaska capable of producing some of the largest earthquakes in the world, the MCE from a local crustal source was calculated to produce a more severe event in terms of on-site ground motions.
than an event on one of those more remote, regional faults due to the substantial attenuation that occurs during propagation from the source to the site.

**Alternatives Assessed and Configuration of Selected Raise**

Several alternatives were investigated for adding the needed tailings storage capacity at the Fort Knox site including: (1) the dam raise adopted for the expansion and described herein, (2) another conventional downstream raise to the TSF dam, (3) a new facility between the TSF and WSR, (4) stacking tailings (paste or filtered) in the upper part of the TSF, and (5) raising the Pearl Creek causeway above its current elevation to form a dam and retaining tailings behind it in the south area of the TSF. However, Alternatives 2 and 3 were eliminated as they would have required more time than available to construct, owing to the large volumes of earth- and rock-fill to be placed at locations with difficult access. Alternative 2 would also have required relocating the downstream seepage collection system. Alternative 4 was eliminated because it would have required a major change to be made to the tailings production, transport, and placement processes with insufficient time to do so. Limitations on the available storage capacity in the upper part of the TSF also made it unattractive. Alternative 5 was eliminated because of limitations on the available storage capacity in the south area of the TSF, which would have required a large raise to the causeway that would have introduced significant construction, geotechnical stability, and surface water management complications. While Alternative 1 had construction, geotechnical stability, and surface water management complications, they were considered to be quite manageable by the design team, and this was proven out in the process. Alternative 1 also offered the advantage of a reduced amount of earth- and rock-fill placement, which correlated directly into a reduced construction cost and duration.

An enlarged cross section showing details of Alternative 1, the selected 52-foot raise, is provided on Figure 3. Key components of the raise include: (1) a base platform fill (grey area on Figure 3) of coarse rock-fill placed into the supernatant pond and tailings upstream of the dam to serve as a foundation for the raise, (2) an excavation into the sloping zones along the upstream face (with the exception of the transition zone) in the original dam above elevation of the base platform fill to reorient those zones towards the upstream, and (3) the raise itself above the base platform fill over the crest and upstream face of the original dam. The top of the base platform fill and bottom of the cut were set at elevation 1466 fmsl, which (along with certain controls on the supernatant pond) allowed for sufficient freeboard to be maintained during construction of the first stage after the cut into the dam was made.

![Figure 3 – Enlarged Cross Section of the 52-Foot Raise (Alternative 1) Adopted for the TSF Dam](image)
Key Design Factors That Enabled This Raise to Be Adopted

One key factor that made the development of this raise against the upstream face of the TSF dam possible was that, at the time of the decision to develop the raise in early 2008, the tailings and surface water levels were well below the crest of the dam, and thus, the large majority of the raise would be constructed on engineered fill within the dam or on its upstream face. Only a small portion of the raise would be built into the pond and over tailings. This configuration allowed the overall stability of the section to meet or exceed industry-accepted standards for large tailings dams, including those of the ADNR Dam Safety Program, even with the low strength tailings in either its static or an earthquake induced liquefied condition. While some small sliver type slips may be experienced on the upstream face of the raise immediately after construction and before buttressing by the rising tailings, no large block or rotational type movements were predicted that could jeopardize the integrity of the raise. A key element of this is that the reoriented seal and filter zones in the raise were positioned to remain over the engineered fill and to be set well back from the extension onto the tailings. This maintenance of stability and integrity independent of the strength of the tailings separates the design of the 52-foot raise from the design of an upstream raise.

A second key factor that made this design possible was the ability to control and draw down the water level and to temporarily limit the rise of tailings against the dam in order to: (1) maintain adequate freeboard when the excavation into the dam was made, and (2) enable the base platform fill to be constructed at as low an elevation as possible. To accomplish this, FGMI converted the area south of the causeway into a temporary excess water storage basin where significant volumes of process reclaim water could be stored remote from the dam and where the large majority of the tailings could be deposited during the period covering the construction of the base platform fill and the excavation and subsequent construction of the first stage of the raise. Hydraulic separation of the south area from the north was achieved by depositing the tailings preferentially from a series of points along a newly established pipeline on the south side of the Pearl Creek causeway to form a continuous elevated beach along this length. FGMI also installed a temporary water transfer pumping system that allowed water to be extracted from the south area and fed, in a controlled manner, to the north where the process water reclaim pumps are located. By placing the majority of tailings into the south area and hydraulically separating the two areas, the only water reporting to the north was from local runoff or controlled transfers from the south, and the process water reclaim pumps were then able to draw down the supernatant pond against the dam. A maximum allowable pond level of 1459 fmsl was established for the period until the fill in the dam was brought back up above the base of the excavation along the entire length of the dam.

Sequence and Timing of Development

The 52-foot raise was designed to be built in a series of stages. In addition to deferring cost, this was beneficial in that it would limit the load applied to the tailings under the upstream side of the raise to a series of modest increments, which would reduce the potential for a slip to occur on the upstream face in response to rapid loading. The first increment of development was the base platform fill that was designed and permitted through the ADNR Dam Safety Program ahead of the remaining stages. Separate and early permitting was sought to enable the platform to be installed as early as possible and, thus, to get it as low as possible against the dam for the reasons described above. Since it was fully contained within the TSF, was well below the crest of the dam, and involved no change to the integrity of the dam an early approval was provided. The subsequent development consists of three stages with crest elevations of 1488 fmsl (to the elevation of the original dam), 1515 fmsl, and 1540 fmsl.

The timeline sequence of development adopted and now being implemented is as follows:
2008 – Geotechnical investigations, and design and permitting of the base platform fill
2009 – Construction of the base platform fill
2008 to early 2011 – Design and permitting of the raise above the base platform fill with early approval of the first stage of raise construction in early 2010
2010 – Construction of the raise to elevation 1488 fmsl including the excavation into the dam at elevation 1466 fmsl
2011 - Construction of the raise to elevation 1515 fmsl (this was underway at the time of writing)
2013 - Construction of the raise to elevation 1540 fmsl

Owing to severe winter conditions at the site, most of the construction is limited to periods between late spring and early fall, which generally covers the months of May through September. However, some rock-fill placement has and will continue to occur slightly earlier or later in each year.

Changes to Tailings Deposition and Surface Water Management

With the small step out onto the tailings deposit and reorientation of the seal and filter zones in the dam, the design team and FGMI agreed that it would be beneficial to revise the tailings deposition and water management practices such that the supernatant pond would be removed from against the dam and replaced with a stiff and drained beach in the future. To accomplish this, the tailings pipeline has been extended down to the dam and is in the process of being further extended along the upstream side of its crest, with off-takes installed at points along the crest, to deposit from the full length of the dam.

In 2010, the pipeline that had been previously extended down the Pearl Creek causeway to deposit tailings forming the hydraulic barrier between the south and north sides of the TSF was relocated to the north side of the causeway. Once the 2010 raise neared completion, tailings were deposited from its end point near the south abutment of the dam, and this formed a large radial beach that extended part way across the face of the dam. Deposition from this location continued through September 2010, and then deposition was shifted south of the causeway through the winter of 2010/2011. In early 2011, the pipe was extended along the upstream side of the southern half of the dam and off-takes were installed to allow for summer spigot deposition to enhance the beach development. Once the 2011 raise to the dam is completed to elevation 1506 fmsl, the pipe will be extended along the northern half of the dam, so that spigot deposition can be advanced into this area for the remainder of the summer of 2011.

Figure 4 shows the development of the beach that has already occurred against the upstream side of the dam from the winter of 2010/2011 discharge at the south abutment and the early summer of 2011 spigot discharge. Future operating plans call for the pipe and spigots to be relocated onto the 1515 fmsl crest to be utilized during the summer of 2012 and then raised up onto the upstream side of the 1540 fmsl crest in 2013 after that raise is completed for on-going summer season spigot deposition.
Investigation of the Tailings Deposit

Since the dam had historically been developed following the downstream method of construction, it had not been necessary to rigorously characterize the strength of the tailings. However, the new 52-foot raise, with its step out onto the tailings, would require incorporation of the tailings undrained strength in its stability analyses. A geotechnical site investigation and laboratory testing program were therefore conducted to allow for evaluation of the liquefaction potential, static shear strength, and post-liquefaction residual undrained strength of the tailings. This evaluation addressed both the coarser-grained tailings sands more remote from the dam and the finer-grained and softer tailings slimes that had accumulated against the upstream face of the dam.

A cone penetration (CPT) testing program was conducted in the summer of 2008 (note this was before the tailings deposition commenced from the dam) using barge mounted equipment in which eleven locations were probed. The majority of the sites were just upstream of the dam in the area of prime interest for the raise and three of the locations, CPT-01, CPT-03 and CPT-07, are shown on Figure 2. The remaining sites were on either side of the Pearl Creek causeway and provided data on tailings upgradient of the dam. The CPT tip data were used to calculate undrained shear strength profiles, and a piezometer in the tip gave information on the in-situ pore pressure conditions after allowing the tip to remain in a fixed position for periods of time. Samples were collected from five of the probe sites to assess index parameters and to provide other data from which the in-situ density was calculated. Geophysical testing was completed at two sites for compression and shear wave (P and S wave) velocities from which low strain shear modulus values were estimated. In addition, advanced geotechnical testing was completed on two large bulk disturbed samples. This test work included flexible wall permeability testing, consolidated undrained triaxial shear strength testing with pore pressure measurements, and cyclic direct simple shear strength testing with a post-cyclic monotonic phase.

The index test results indicated two distinct material types comprising: (1) a fine-grained non-plastic to low plasticity silt (slimes), and (2) a more coarsely graded non-plastic sandy silt to silty sand. The slimes were consistently found adjacent to the dam while inter-layered slimes and sandy silt materials were found adjacent to the causeway. These findings are consistent with the method of deposition of the tailings from open ended pipes on the west side of the TSF. The two different materials gave differing dry density profiles with the slimes ranging from 69.6 to 89.0 pounds per cubic foot (pcf) and the sandy silt ranging from 85.9 to 106.5 pcf. These data bracket the generally accepted average dry unit weight of 85.9 pcf used for the TSF from known mill tonnages and volume calculations from...
topographic and bathymetric surveys. The pore pressure measurements indicated that near hydrostatic conditions were present within the tailings just upstream of the dam.

The undrained strength of the slimes was estimated using the procedure outlined by Olsen and Stark (2002). The strength profile results for the data at CPT-01, CPT-03 and CPT-07 gave a ratio of $\frac{S_u(\text{yield})}{\sigma_v'}=0.22$, which was selected for use in the slope stability analyses representing conditions immediately following the construction of the base platform fill. The post-cyclic undrained strength ratio for the slimes was found to be very low $\frac{S_u(\text{liq})}{\sigma_v'}=0.04$, and this value was used in the post-cyclic stability analyses of the raised dam.

Figure 5 below shows the CPT testing underway from the barge at a location just upstream of the TSF dam.

![Figure 5 – CPT Testing Underway from the Barge Just Upstream of the Dam](image)

**Base Platform Fill Design, Construction, and Performance**

The base platform fill was constructed out of coarse, clean granitic waste rock from the mine. The work was completed in two parallel, south to north advancing zones described as follows:

- **Zone 1** – Immediately adjacent to, and founded solely on, the upstream sloping face of the dam. The placement of rock-fill into this zone did not displace any tailings.

- **Zone 2** – Immediately adjacent to but upstream (west) of Zone 1 in the TSF and founded on tailings. The placement of rock-fill into this zone displaced tailings.

Loaded trucks delivered the rock to the point of placement in the fill by exiting from the Pearl Creek causeway at the south end of the fill and traveling north on the surface of Zone 1. Empty trucks were allowed to run on Zone 2 only to accommodate the passage of a loaded truck in Zone 1, otherwise all truck traffic was kept in Zone 1. Loaded truck traffic was not permitted to run in Zone 2. Zone 1 was generally advanced slightly ahead (north) of Zone 2 and the following paragraphs describe the fill placement sequence and procedures in each zone.

- **Zone 1** - Just prior to reaching the end of the south to north advancing face of the fill in Zone 1 the trucks turned and dumped the material into piles on the upper surface of the active lift. A dozer then pushed the material further north to form the next south to north increment of fill. Once advanced to a point approximately 50 feet north of Zone 2, the fill placement was switched into Zone 2 (procedure described below) to bring it up to and even with Zone 1 before Zone 1 was advanced another 50 foot increment and the process was repeated.
Zone 2 - The trucks dumped the material into piles on the surface of the recently advanced increment of Zone 1 fill. The dozer, working in an east to west direction, pushed the material towards the west (away from the dam) until the upstream limit on the base platform fill was reached. In general, the dozer advanced the fill progressively northwards in Zone 2 in a series of east to west strips such that any one strip was completed before the next one to the north was commenced.

Rock-fill placement into Zone 2 involved intentionally failing the soft tailings to achieve a large depth of penetration that would place more fill over the sloping upstream face of the existing dam. This added to the overall stability of the completed raise. The main objective of the east to west strips was to displace a mud wave from the failed tailings to the west into the TSF. If Zone 2 had been constructed simply by advancing the fill from south to north like Zone 1, the mud wave would have been displaced to the north and would have remained in front of the fill, which would have limited the depth of penetration of the rock-fill. Large rock-fill berms were maintained at the advancing fronts of each zone for both safety and to add a surcharge load to the advancing face to assist in failing the tailings. Compaction of the rock-fill was accomplished in Zone 1 by routing the loaded haul trucks evenly over the surface of this zone. In Zone 2, compaction was accomplished by the dozer. These procedures worked well and no trafficability or safety difficulties were experienced by the truck or dozer crews. Figures 6 and 7 illustrate the construction.

The depth of rock penetration into the tailings was estimated prior to construction by completing a series of limit equilibrium slope stability analyses. In these analyses, the rock-fill of the base platform fill was extended down into the tailings to different depths and the assumed depth that resulted in a factor of safety of unity was considered the design depth, which was approximately 25 feet. The theory was that the rock-fill would advance downward to a point where its mass would just become supported by the mobilized undrained strength of the soft tailings below, and this strength was noted to increase with depth as reported earlier. This design depth compared well with a post-construction estimate made from the volume of rock-fill placed into the work and the width and elevation of the platform. Further support for this depth was provided from a series of five drill holes that were advanced through the platform in 2010 to install piezometers into the underlying tailings to monitor for construction-induced excess pore pressures as the subsequent stages of the raise were built.

The base platform fill was completed late in 2009 and was left over the winter of 2009/2010 to allow the underlying tailings to dissipate any excess pore pressures and the platform to take up any resultant settlements. After the snow had melted in the spring of 2010, the surface was inspected, and minor longitudinal cracks were observed running in a south to north direction along the approximate boundary between Zones 1 and 2. The surface of Zone 2 was also noted to have rotated slightly downward along its upstream edge. These findings are consistent with the tailings in the triangular shaped wedge under Zone 2 having consolidated and were thus expected. Prior to construction of the subsequent raise in 2010, the cracked area was ripped with a dozer, and a small amount of rock-fill was placed over Zone 2 to restore its surface to elevation 1466 fmsl.
Figure 6 – View Looking North Showing Construction of Zone 2 of the Base Platform Fill with a Tailings Mud Wave Displaced to the West

Figure 7 – View Looking South Showing Construction of the Base Platform Fill without a Tailings Mud Wave Displaced to the North in Front of the Advancing Fill

Raise Design, Construction and Performance

The dam raise above the base platform fill is shown on Figure 3 and was constructed using materials and specifications that were similar to the original dam. Weathered schist was utilized in the seal zone, weathered granite in the filter zones, and competent rock-fill from the mine was used in the transition zone and rock-fill shells. The first stage of the dam raise above the base platform fill was completed in the summer of 2010 and involved excavating into the upstream side of the dam down to elevation 1466 fmsl, and then placing fill back into the excavation and over the top of the base platform fill to reorient the seal and filter zones. A large amount of the excavated seal and filter zone materials were reused after temporarily stockpiling them on the Pearl Creek causeway. By the end of the summer construction season in 2010, the raise was completed to elevation 1488 fmsl, which re-established the crest of the dam back at its original, post 2006 level. Construction is now underway in the summer of 2011 on the next stage of the raise to elevation 1515 fmsl, which represents the first stage above the post 2006 level. This is expected to be completed in September 2011.

Performance to date has been good. Similar to the findings on the base platform fill in early 2010, some minor cracking and a very slight deformation of the upstream portion of the fill was observed in
early 2011 on the 1488 fmsl crest. However, this cracking and rotation was limited to within the upstream rock-fill shell and well removed from the filter and seal zones. No significant deformations or sloughing of the upstream face have been observed, although the design slope stability analyses indicated that some limited and non-consequential sloughing could occur either under post-construction or post-earthquake conditions. In general, the fill has remained sound, intact, and stable.

Extensive finite element seepage analyses; static, post-construction, and post-earthquake stability analyses; and dynamic (earthquake) deformation analyses were completed for the design of the 52-foot raise. The seepage analyses were used to define pore pressures for use in the stability analyses. They showed that the primary flow path is within the upstream rock-fill shell and filter zone into the fractured bedrock foundation and then beneath the seal zone to the seepage collection system at the downstream toe. The seal zone limits seepage through the embankment into the downstream filter zone and rock-fill shell to small amounts such that the downstream shell remains unsaturated, which is a key design objective. The results of an analysis on the original dam section compared well with measured seepage flow rates and pore pressures to date indicating that the model was well calibrated. The results of the analyses with the 52-foot raise in place and the tailings level increased in front of it indicate that the downstream shell can be expected to remain unsaturated.

Upstream and downstream factors of safety from the static limit equilibrium slope stability analyses were found to meet or exceed the values required for large tailings dams. Under post-earthquake conditions, the factors of safety were found to meet or exceed those required for large tailings dams on the crest and downstream slope, even considering liquefaction of the impounded tailings. Analyses on the upstream face indicated that some shallow, localized minor movement could be experienced during the 2010 construction work or upon the occurrence of strong earthquake shaking shortly after the 2010 or 2011 construction stages. Such movement would not reduce the overall stability of the dam, or impact the integrity of the filter or seal zones, nor would it reduce the freeboard provided by the dam, and repairs would simply involve localized regrading/reconstruction of the upstream slope. The risk of any significant movement was found to diminish markedly from the 2010 to the 2011 arrangement and be virtually eliminated for the 2013 arrangement with the tailings beach buttressing the upstream face.

Results of the permanent earthquake-induced deformation analyses indicate that vertical settlements and horizontal displacements along the crest of the embankment, including the tops of the engineered zones, are expected to be very small (less than a foot). Since the center of the embankment will be overbuilt by the 3.0 foot camber, there is little risk of any loss of freeboard. Furthermore, given the horizontal width of the filter and seal zones, there is little or no chance that such small deformations would compromise their continuity, integrity, or function.

Summary and Conclusions

The Fort Knox TSF is being expanded above its originally planned capacity to accommodate additional tailings. A site wide optimization study identified a 52-foot raise to the dam as the preferred alternative, and an innovative approach to the raise, involving placing most of the raise on the original embankment, with only a modest step out onto the tailings, was adopted. This enabled a high level of stability and security to be maintained in accordance with good industry practice and ADNR Dam Safety Program requirements without adopting a conventional downstream raise that would have required a new zone of fill to be constructed from the downstream toe of the dam to the raised crest at considerable cost and an extended duration. State-of-the-art finite element seepage analyses; static, post-construction, and post-earthquake stability analyses; and dynamic (earthquake) deformation analyses were completed for the design to confirm its adequacy.
Key components of the raise include: (1) a base platform fill of coarse mine rock-fill placed into the supernatant pond and tailings upstream of the dam to serve as a foundation, (2) an excavation into the upstream sloping zones in the original dam above the base platform fill to reorient them towards the upstream, and (3) the raise itself above the base platform fill. An additional key component is the development of a stiff and drained tailings beach against the upstream side of the raised dam.

The base platform fill was completed in 2009, and the first stage of the raise was completed in 2010 to bring the crest of the dam back up to its original elevation of 1488 fmsl and to reorient the upstream sloping zones. The second stage of the raise was underway at the time of writing (summer of 2011) and will elevate the crest to 1515 fmsl when completed. The third and final stage will be constructed in 2013 to establish the crest at 1540 fmsl. Performance to date has been good. Some cracking and minor deformation of the fill placed over the tailings has been observed but was expected. No issues of concern have been noted, either visually or from the piezometers, flow meters, and deformation gages in the dam.

References


