Mine Closure 2011 — A.B. Fourie, M. Tibbett and A. Beersing (eds)

doi:10.36487/ACG_rep/1152_38_Mao

Closure of tailings dams

Y. Mao *Golder Associates Ltd., Canada*

S. Kam *Golder Associates Ltd., Canada*

Abstract

The preparation of tailings dams for closure is described in a mine closure plan that is typically prepared a number of years prior to mine closure. Tailings dams typically follow short term design criteria during the operational stage and then transition to comply with long term design criteria when they are prepared for the closure stage. Transition usually requires follow-up works which may not be foreseeable during the development of the closure plan. Changing site conditions and regulatory environment also are major factors to consider in closure planning for tailings dams. Late realisation of closure work components may contribute to an underestimation of closure costs and may result in delays in implementing closure.

Previous experiences in tailings dam closure can provide useful information to better assist with closure planning. Unless fully decommissioned or removed, tailings dams must remain stable and serve their intended function to safeguard the environment over the long term. The long service life of closed tailings dams merits careful consideration in design for closure. This paper provides an overview of some typical closure work components for tailings dams. Examples on carrying out these work components are discussed. It is the authors' intention to outline a framework that may assist with early stage closure planning based on known and expected future conditions, so as to minimise project risk for closure of tailings dams.

The closure of tailings dams often involves four stages: (1) Investigative components, including geotechnical, environmental, hydrological and biological characterisation programmes to determine the need and the type of work components required for a dam; (2) Routine monitoring components, ranging from dam safety inspections, dam safety reviews to various monitoring programmes to evaluate the condition and performance of the dam; (3) Physical components of a dam that require upgrading to improve stability, pond and seepage conditions, aesthetics, spillway and drainage channel configurations, etc., (as determined from stages (1) and (2)); and, (4) Long-term management components, including care, maintenance and surveillance and managing corporate knowledge of the facility.

1 Introduction

The principal criterion of preparing tailings dams for closure is to ensure that dam performance is not jeopardised over the long term. Dam performance includes factors such as structural stability, the ability to retain solids and fluid in accordance with the design, storm runoff control and erosion prevention, etc. In some situations the aesthetics of dam is an important consideration for closure. These performance factors should be evaluated for closure planning and the need for the tailings dams to undergo upgrades or modifications identified. Once the physical component upgrades are in place, requirements on surveillance and maintenance works should be developed in a long term tailings dam safety management plan. Actual surveillance and maintenance works should then be carried out on a regular basis according to the plan to ensure that the dams continue to perform as intended.

In general, tailings dam closure works are carried out in stages and involve the following components:

- Investigative components and routine monitoring components to provide information regarding condition and performance of the tailings dams.
- Physical components of the dams that, based on results from investigative and monitoring components, require upgrades or modifications in order to satisfy closure requirements.
- Long-term management components that include care, maintenance and surveillance, site access and security, as well as proper documentation of the dams.

This paper outlines some typical closure work components for tailings dams. Information on the need and the type of closure work required should be obtained during mine operation to allow early stage planning and implementation to minimise closure requirements. It should be recognised that tailings dam closure preparation is typically one of the many components of a much larger effort to return the mine facility to an environmentally acceptable state. Closure works carried out during operation can be implemented into a progressive mine rehabilitation plan.

2 Closure design for tailings dams

Modern tailings dam design practices in Canada and in many parts of the world require that tailings dams be designed for closure. Closure plan preparation is mandatory in many jurisdictions and required by many financial institutions for project funding. However, during the operating period some tailings dams may be designed with less stringent criteria with the expectation that the risk of failure or poor performance would be acceptable given the relatively short operating period. These structures will need to undergo a greater degree of preparation to meet closure requirements.

Closure of tailings dams involves preparing the dams and their supporting structures into a configuration that will ensure stability in the long term. The tailings dams have to remain serviceable during extreme disruptive events such as floods and earthquakes. Guidelines for the design tailings dams for closure are well established in many jurisdictions in Canada. The ‘Dam Safety Guidelines’ published by the Canadian Dam Association (CDA, 2007) is widely used for the design and management of dams. When designing tailings dams for closure, typical engineering practice follows the procedures below:

- Classify the dams based on potential failure consequences (sometimes known as hazard potential).
- Develop design criteria based on the consequence category assigned. These criteria typically include the following:
  - Design earthquake event.
  - Design inflow flood event.
  - Requirements for routine maintenance and surveillance, periodic safety reviews and emergency preparedness.

The potential failure consequences are assessed in terms of public safety risk, environmental and cultural impacts, and financial losses. These factors can and often change throughout the mine life and even after mine decommissioning. Some common issues that may affect dam classification include land development around and downstream of the dam, and change in social acceptance. It is therefore critical that the failure consequences classification be reviewed when preparing design for closure.

The closure dam design should be developed based on performance of the dam. This is most critical as many tailings dams are built over time, under variable site conditions that may deviate from the original design. Data gathering may entail the following:

- Review existing geotechnical data or carry out additional investigation programmes to obtain sufficient foundation and dam fill material parameters for dam stability assessment.
- Assess dam performance with respect to its ability to minimise environmental impact to surface and groundwater.
- Review existing environmental data or carry out additional sampling programme to obtain sufficient water quality and geochemistry information to assist in performance upgrades and modifications of tailings dams for closure.

2.1 Dam classification

Tailings dams will have to remain stable during and following a design earthquake condition; and either containing or safely conveying runoff under the design flood condition. These design conditions are developed to minimise the likelihood of a dam failure. To assist on selecting design conditions, common engineering practice involves classifying dams into categories based on the expected failure consequences in case dam failure occurs. Categories typically include levels such as "Low", "Significant", "High", "Very High" and "Extreme" as failure consequences become increasingly severe. As an example CDA (2007) consequences include loss of life, losses on environmental and cultural values, as well as losses on infrastructure and on the economy. Dams are required to sustain higher earthquake and storm events when the consequences of a dam failure are more severe.

It should be noted that current failure consequence approach is a well accepted practice for dam design. However, with a much longer service life tailings dams may pose a greater risk of failure than conventional dams. Some of the factors that contribute to a greater failure risk for tailings dams include:

- Long exposure period (thousands of years).
- Uncertainty on maintenance and surveillance in the long term.
- Effect of climate change on extreme events.
- Chemical stability of the impounded tailings or water.

The long service life for tailings dams is by far the most important consideration as the likelihood of exceedance for a given design event increases with the design life as illustrated in Figure 1. It is clear that to achieve the same reliability for a conventional dam with a shorter design life a tailings dam will have to be designed to higher loading criteria. With reference to guidelines provided in CDA (2007), it is recommended that the upper range of the recommended flood and seismic loadings be adopted for tailings dam closure design.

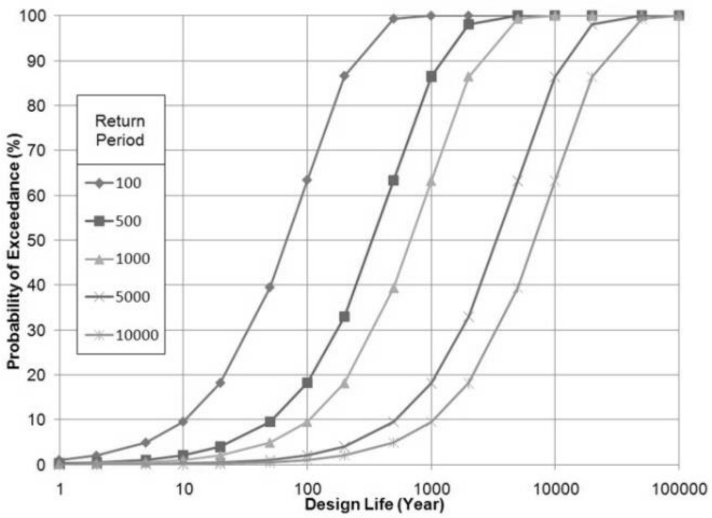

Figure 1 Relationship between design life, return period and probability of exceedance

2.2 Design earthquake event

A design earthquake event is the earthquake event that the tailings dams in consideration are required to sustain without inducing failure to the overall dam structure. It is described according to return periods, where shorter return periods represent smaller events with more frequent occurrence, while longer return periods represent larger events with less frequent occurrence. Typical design earthquake return periods for tailings dams range from 500 years during mine operation to 10,000 years for closure, depending on dam classification.

2.3 Design inflow flood event

The design inflow flood event is the rainfall and/or snowmelt runoff event(s) that the tailings dams and associated conveyance structures should be designed to pass safely without inducing erosion to the overall dam structure. Flood events are also described according to return periods. Typical design flood return periods ranges from 100 years for internal water management up to the probable maximum flood (PMF) at major discharge locations and containment areas.

2.4 Factor of safety

Factor of Safety (FoS) is defined as the structural capacity to resist failure divided by the loads contributing to failure. For example an FoS of 1.0 implies that the failure resisting capacity equals to the failure contributing loads. In engineering practice, dams must be designed with an FoS higher than 1.0 to incorporate adequate amount of conservatism, and to provide sufficient buffering capacity to accommodate possible variations on foundation and fill material parameters. CDA (2007) provides guidance regarding minimum FoS required under various loading conditions. Design of tailings dams generally follows the criteria for water retaining earth embankments. Recommended FoS for various loading conditions are summarised as follows:

- Drained or long term, under effective stress condition:
  - Static loading – FoS = 1.5.
  - Pseudo-static loading – FoS = 1.0.
  - End of construction or unusual loading – FoS = 1.2 to 1.3.
- Undrained or short term, under total stress condition:
  - Static loading – FoS = 1.3.
  - Pseudo-static loading – FoS = 1.0.
  - End of construction or unusual loading – FoS = 1.2 to 1.3.

Selection of either a drained or an undrained condition for a dam depends on foundation soil type, dam fill material and the phreatic surface. Closure design should focus on long term drained condition, while short term undrained condition should be analysed to ensure that foundation stability is maintained during and immediately following the construction of closure components.

Static loading scenarios examine the stability of dams under the weight of the dam fill and the level of the phreatic surface. Pseudo-static loading scenarios introduce horizontal ground acceleration as an additional loading onto the dams to simulate earthquake motions. Peak horizontal ground accelerations at the top of bedrock for a range of earthquake return periods across Canada are determined by geological surveys and are published by the government under the National Building Code of Canada. Attenuation of the ground motion through the overburden column can be estimated based on soil strata information and numerical simulation.

Strong earthquake excitation can cause a build up of pore water pressure in some saturated soils leading to a decrease in the shear strength. The likelihood of liquefaction in the dam structure or in its foundation should be investigated.

3 Closure components

Several work components are typically required to prepare tailings dams for modifications from the operation phase to the closure phase. In some occasions dam closure upgrades can be planned and carried out prior to mine closure. This section outlines the four main work components to prepare tailings dams for closure.

3.1 Investigative components

Typical investigative works include geotechnical and environmental sampling programmes, as well as performance assessment studies. These programmes and studies are set up to gather the necessary information related to the engineering and environmental aspects of the tailings dams.

3.1.1 Geotechnical investigation programme

Where there is inadequate information on the tailings dam and its foundation, geotechnical investigations are typically carried out. This work may involve test pitting, borehole drilling, water permeability testing, as well as piezometer and instrumentation installations on and around the vicinity of tailings dams. Subsurface soil conditions and appropriate design parameters should be developed from a field and laboratory testing programme. Geotechnical instrumentation could be valuable tool to validate dam performance.

3.1.2 Environmental study

Environmental studies examine surface and groundwater qualities, groundwater flow behaviour, as well as the geochemistry of sediments and precipitates. At the closure phase additional environmental monitoring may be required. Findings from the environmental study will assist planning for the transition and closure phases on typical items such as water treatment requirements, as well as the need to construct additional holding ponds around the tailings dams for seepage quantity control or quality improvement. The most direct impact of environmental studies on the closure of tailings dams is whether additional measures such as grouting or cut off construction is required to control dam seepage and enhance overall dam stability.

3.1.3 Hydrological assessment

It is often the case that site drainage will be altered at closure. These changes affect the hydrological design of the tailings dams and hydraulic structures, and should be taken into consideration as part of tailings dam closure planning. Hydrological assessment involves gathering surface water flow information to develop a closure phase water management plan for the overall tailings area or the entire mine site. Hydrological items that will affect tailings dams generally include, but are not limited to, the following:

- A water cover over deposited tailings for closure implies that the tailings dams will be subjected to an elevated water head and occasional wave action for the long term.
- Runoff diversions around the tailings area during operation phase may require removal, resulting in a larger watershed contributing to larger runoff towards the tailings dams and spillway.
- Drainage upstream of the tailings dam.

3.2 Routine monitoring components

Monitoring components includes various routine environmental monitoring and dam safety inspection programmes. These programmes are usually in place throughout the operation phase to provide up-to-date knowledge on the condition of the tailings dams. It also provides historic records on dam performance for future references that are useful in the closure design. The need and the type of work components required for dam closure modification can be determined based on findings from monitoring and inspection programmes.

3.2.1 Environmental monitoring programmes

Routine water quality and flow monitoring programmes can provide information on performance items such as seepage quality and flow quantities at the tailings dams and associated hydraulic structures. Performance upgrades and other modifications can be designed according to findings from these environmental monitoring programmes. These routine programmes can also provide background and historic information to enhance design accuracy on predictions and extrapolations for future planning purposes.

3.2.2 Dam safety inspection and dam safety review

Dam safety inspections of the tailings dams, the associated hydraulic structures are usually carried out periodically. Dam instrumentation monitoring provides early detection of changing condition in the dams. Further studies may be required to identify the reason(s) for the condition change, and to prepare remediation or upgrading works that follow. The main focus of an inspection is to confirm the stability of the tailings dams and the proper functioning of the hydraulic structures, as well as to provide a record of performance information.

The requirements for inspection and review for tailings dams may reduce with time with demonstrated performance. For dams that may remain a safety or environmental hazard after closure, dam safety reviews may be required every 5–10 years, depending on specific conditions of the dams, and involves the following:

- Carry out a dam safety inspection.
- Conduct a thorough review of the following information and documents:
  - Existing dam operation data and record.
  - Consequences of dam failure, such as when the downstream conditions have changed from the previous review.
  - Design and construction record of the tailings dams and all associated structures.
  - Operation, maintenance and surveillance (OMS) manual.
  - Emergency preparedness plan (EPP).
  - Public safety and site security measures.
  - Dam safety management system, such as policy development, management plan, action procedures and record keeping, etc.

3.3 Physical components

The closure design may include modifications to the existing dam configuration as well as additions of supporting physical components. Examples of some physical components that are typically applied to prepare tailings dams for closure are summarised in this section. In some cases, such as seismic retrofitting may require a combination of rehabilitation techniques. To achieve closure objective (e.g. maintaining tailings saturation or tailings containment) some tailings dams are raised and some new dams may be built.

3.3.1 Toe reinforcement

Toe reinforcement is a common method to improve the stability and to prevent toe erosion of tailings dams. A toe berm acts as a counter-balancing weight in resisting potential slip failure of the tailings dam. A toe berm is generally recommended when stability of the dams is marginal, i.e. FoS is less than the required values stated in Section 2.4. Toe berm should preferably be constructed with free draining granular materials such as blast rock or sand and gravel.

Figure 2 shows the construction of a 300 m long toe berm for a closed mine in southeastern Ontario. The 5 m wide toe berm was constructed to half the height of the 8 m high tailings dam to provide additional stability buffer against seismic loading. Sand and gravel forms the bulk of the structure while quarried rock was placed on the surface and slope face as erosion protection.

(a) (b) (c)

Figure 2 Toe berm construction: (a) foundation; (b) internal zones; (c) completed toe berm

Toe stabilisation generally involves placing rockfill or rip rap along the lower portion of a tailings dam to prevent erosion. Where there is excessive seepage at the toe of the dam an inverted filter can be incorporated in the toe berm to reduce the likelihood of erosion. Seepages day-lighting along the toe of tailings dams may contribute to local erosion, which, if remediation is not done immediately, may develop into larger retrogressive erosions propagating towards the upper and inner portion of the tailings dam.

3.3.2 Slope re-grading

Slope re-grading reduces the overall profile of the tailings dam to achieve the desired stability. This method is commonly used in homogeneous dams such as those constructed with tailings. Figure 3(a) is a typical tailings dam with a steep downstream slope. Excavating the upper part of the slope and placing fill at the dam toe can result a gentle slope profile suitable for revegetation as shown in Figure 3(b).

(a) **(b)**

Figure 3 Tailings dam slope re-grading: (a) prior to re-grading; (b) after re-grading

Some tailings dams are raised in lifts by the upstream method, either with borrowed fill or with tailings. The starter dams are typically founded on competent ground, while the raised lifts are usually founded on deposited tailings. Due to concerns on foundation strength for the raised lifts, modern practices usually involve raising the dams with an offset from the previous lift to create a gentler slope for the overall configuration of the tailings stack. Some old tailings facilities did not provide sufficient offsetting distances between lifts, which may be acceptable during operation phase, but will require re-grading to satisfy long term closure requirements. Typical overall slope of the stack should be at least 2.5(H):1(V) to 3(H):1(V), or flatter if the dams are constructed with tailings. Figures 4 and 5 show the schematic layouts of tailings dams raised by the upstream method. On Figure 4 the tailings dam lifts are constructed with granular fill. In Figure 5 the tailings dam lifts are constructed with tailings excavated from the adjacent beach, and as a result the offsetting distance between each lifts is greater to create a gentler overall slope surface to ensure long term stability.

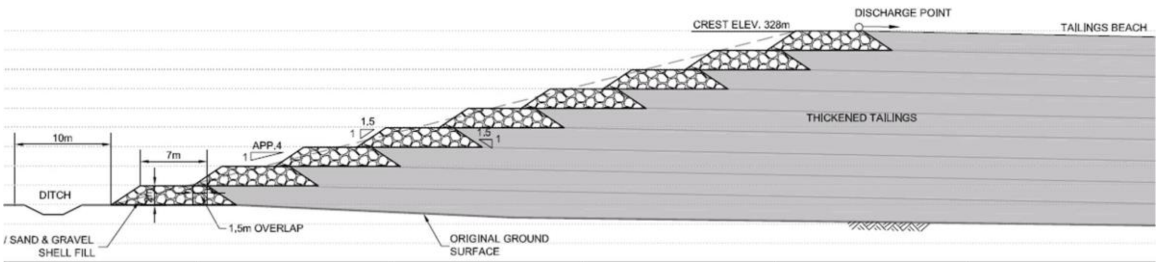

Figure 4 Typical upstream raise of tailings dams with granular fill

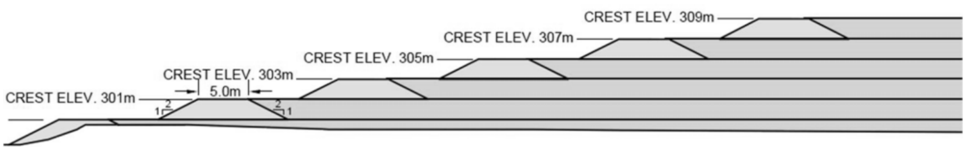

Figure 5 Typical upstream raise of tailings dams with beached tailings with wider offset

At closure, it is common practice to smooth the individual lift benches into a continuous slope across the entire height of the tailings facility. For tailings dams that were raised without an offset distance, the overall slope will have to be flattened to provide adequate long term slope stability. Drainage ditches can also be incorporated in the finished slope. Several advantages can be realised with re-grading a tailings dam slope face:

- Reduce the likelihood of local surface erosion from developing into larger scale retrogressive erosion that affects a larger area.
- Allow installation of a closure cover.
- Encourage seeding and re-vegetation.
- Enhance the overall aesthetic of the tailings stack.
- A continuous slope allows easier access for maintenance and surveillance.

3.3.3 Erosion protection upgrade

Tailings dams that are constructed with tailings are typically more susceptible to erosion. This type of dams are constructed either by direct deposition of cycloned underflow along the perimeter of the tailings facility, or by excavating previously developed tailings beaches to construct new lifts. The degrees of compaction of these tailings dams are generally nominal.

To prepare these tailings dams for closure, slope re-grading can be carried out to re-configure the downstream face of the dam into a continuous slope as described in Section 3.3.2.

In the case that infiltration through tailings does not adversely affect downstream water quality, a granular erosion prevention cover can be constructed. The granular cover consists of sand and gravel and/or cobbles and boulder size rip rap. These coarse materials are more resistant to erosion than tailings. A tailings dam that was re-graded and lined with granular rocks is shown in Figure 6. A series of swales can be added to the tailings dam slope to facilitate drainage. Placement of rockfill on slope reduces vegetative growth and therefore maintenance.

Figure 6 Rockfill is typically used as erosion protection on dam surfaces

3.3.4 Dam replacement

In the case that the tailings may adversely impact the environment, infiltration into and seepage from the tailings facility should be minimised for closure. Tailings dams constructed either with tailings or with granular materials are largely free draining and do not meet the objective of minimising infiltration or seepage.

Figure 7 shows an example of a replacement dam for a closed mine where a new, low permeability dam was constructed downstream of a tailings stack. The original tailings dam slope face was buttressed by the new dam, which was constructed with a till core and granular dam shell on the downstream side. The dam eliminated dusting issue, provided a barrier against the outflow of impacted seepage and enhanced the stability of the tailings stack.

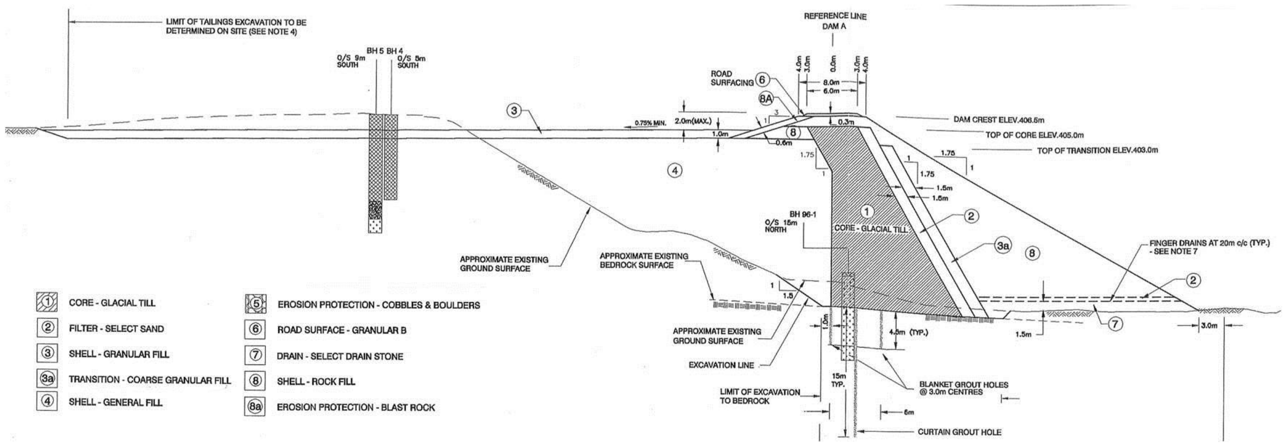

Figure 7 A typical dam replacement design to re-construct the tailings boundary

3.3.5 Vegetation

Vegetation on the dam face should be controlled as root penetration into the dam may affect dam integrity especially in water retaining dams that incorporate a low permeability zone for water retention. The presence of vegetation also hinders visual inspection of the dams. In general, low lying shrub type plants do not have deep roots, while trees should be removed to avoid root penetration from reaching the dam core.

3.3.6 Dam decommissioning

Some mining dams especially those associated with diversion or water management systems are breached at closure to restore the original site drainage. Some tailings dams may also be removed as part of site re-grading.

3.3.7 Tailings dams that accommodate water cover

Some tailings facilities are designed with a water cover at the closure phase to keep tailings saturated and prevent acid generation. Design requirements for tailings dams that retain a water cover are largely similar to the low permeability dam discussed in Section 3.3.4. The dam must in addition meet freeboard requirement and be protected with riprap or rockfill against wave action. Figure 8 shows a tailings facility that utilises a water cover at closure. The upstream slope face of the tailings dam is lined with rip rap.

Figure 8 Typical upstream erosion protection for a tailings facility with a water cover

3.3.8 Hydraulic structures

All hydraulic structures should be modified to minimise maintenance and risk of blockage following closure. Often culverts and decant structures are removed and replaced with open spillways. The durability of the drainage facility should also be considered for closure. Some mines are located in climatic regions that stipulate water discharge to the environment can only be carried out during particular seasons. Hydraulic structures for the closure of these mines should accommodate fluctuations in water level. Typical engineering design utilises stoplog structures for this purpose. Figure 9 shows a stoplog constructed across an outlet spillway for a tailings dam.

(a) (b)

Figure 9 Typical stoplog structure: (a) downstream view; (b) upstream view

At closure, the spillway invert for a tailings dam can be set to withhold a tailings pond for a water cover, or it can be lowered to drain the tailings pond used during operation to allow installation of a dry cover. Figure 10(a) shows a closure spillway that regulates the pond level for a closed mine. This tailings facility incorporates a combination of re-vegetated dry cover close to the tailings dam to avoid direct ponding against the dam, while maintaining a sub-aqueous pond further into the centre of the tailings facility, as shown in Figures 10(b) and 10(c).

(a) (b) (c)

Figure 10 (a) Spillway invert; (b) dry cover; (c) sub-aqueous pond in centre of tailings facility

Spillway blockage by beaver activity, fallen vegetation or debris accumulation is a major concern. Some spillways have been designed to either discourage beaver activity or to facilitate maintenance. Often redundant flow conveyance is provided usually in the form of a dry spillway to safeguard the dam.

Water quality and flow monitoring may continue for a period of time in the closure phase. Construction and installation of monitoring weir or flume structures may be required. Figure 11 shows a combined structure of decant channel and storm conveying spillway for a closed mine. The decant incorporates flow measuring devices to handle and measure normal flows, while the adjacent spillway to provide safe conveyance for the inflow design flood.

(a) (b)

Figure 11 (a) Decant channel; (b) storm spillway

3.4 Long term management components

Once the physical modifications and upgrading works are completed for the tailings dams and the associated hydraulic structures, a long term management plan should be developed to ensure the dams continue to function properly for the long term. Components that require consideration in a long term management plan should include developing a manual or protocol to standardise the following:

- The frequency and focus of dam performance surveillance programmes. Surveillance should include:
  - Observation of any signs of dam instability, such as slope movement, crest settlement, erosion, surface rilling or unravelling, etc.
  - Observation of flow conditions of hydraulic structures, particularly focussing on any blockages.
  - Carry out measurements and record dam instrumentation and hydraulic structure flow measurement data.
  - Prepare and properly archive all surveillance results.
- Perform periodic maintenance such as vegetation control on dams and carry out remediation on an as required basis.
- Develop a hierarchy structure of the members in a dam safety management team and assign responsibilities to each team members to ensure the long term management plan is properly

executed. Such a programme could include periodic inspections by an engineer and periodic dam safety reviews.

- Maintain site access and security.

4 Conclusion

Considerations on preparing tailings dams for the mine closure phase were discussed in this paper. Design criteria for the long term structural stability and hydraulic performance of tailings dams were outlined. The planning of closure activities for tailings dams often should start with investigations and study programmes to identify the need for upgrades and modifications taking into consideration changes to the tailings dams and the downstream environment. The lack of maintenance is a concern for many tailings dams following closure. These structures should be designed for minimal maintenance and with redundant flow conveyance capacity and stability.

It is the intention of the authors of this paper to provide mine operators a brief summary of typical work components required for tailings dam closure. By early identification of these work components, closure preparation can be planned, budgeted for, and in some occasion be carried out in advance under a progressive mine rehabilitation plan for a portion of the mine site.

Reference

CDA (2007) Canadian Dam Association. Dam Safety Guidelines, Canadian Dam Association, 82 p.