Hydrologic Closure of Mine Tailings Facilities

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Abstract

This paper presents a hydrologic closure design concept to minimize the risk of water discharges from closed mine tailings facilities. It evaluates the applicability of U.S. Nuclear Regulatory Commission guidelines to develop acceptable designs for the closure of tailings facilities that have a calculated adequate surcharge capacity for environmental protection and an emergency spillway for dam safety. The guidelines provide a basis to estimate an acceptable surcharge capacity of a Probable Maximum Flood series for storage of surface runoff. To be conservative and for redundancy with respect to dam safety, an emergency spillway is provided to pass the Probable Maximum Precipitation. Depending on the annual water balance, the surcharge capacity may be used by surface runoff and minor amounts of sediment that accumulates in the impoundment from year to year. The emergency spillway crest is then set at this level or above the surcharge capacity, whichever is higher. An example is given of the active Red Dog Mine tailings facility in Alaska where this method was used for the preliminary design of the tailings main dam at its ultimate closure configuration.

Introduction

There are old, abandoned, dry and wet solid waste disposal facilities worldwide that require environmentally acceptable closure. These include abandoned mine tailings facilities and process waste settling basins. Also, many existing mines must plan for future closure of tailings ponds. Safe closure of such facilities requires a goal of zero discharge in perpetuity. Generally, passive operations are preferred with no pumping, treatment, and discharge. Conversely, dam safety regulations require that tailings ponds with dams have an emergency spillway that can pass an extreme storm event.

A solution is offered to address a spillway dilemma for mine tailings closures – the dam needs enough freeboard to prevent overtopping and discharge to the environment - but dam regulations require a spillway to prevent the dam from overtopping and provide a means for discharge. These are somewhat contradictory viewpoints. Therefore, the objective of this paper is to present an approach to defining a reasonable methodology for determining the storage capacity of the facility above the final tailings level without passing any flow through the emergency spillway.

Red Dog Mine is a zinc and lead mine in northwest Alaska. It is operated by Teck Alaska Incorporated (Teck) and owned by Northwest Alaska Native Association (NANA) Regional Corporation. The mine is located in the Northwest Arctic Borough of Alaska near the southwestern end of the DeLong Mountains of the western Brooks Range, approximately 145 kilometers north of the Arctic Circle, 132 kilometers north of Kotzebue, and 76 kilometers inland from the Chukchi Sea. Mine operations started in 1988 and mine closure is planned for around 2030. The main components of the mine are:

- Open pit mine for the extraction of metal bearing ore
- Mill and concentrate facility
- Tailings facility that is contained by a tailings main dam and a saddle (back) dam
The tailings main dam is an approximately 60-meter high rock fill. For seepage control, the dam has a liner system with a geomembrane that extends down to relatively competent bedrock. Current plans are for the dam to be raised by an additional 5 meters before closure. The tailings facility and dam will require an environmentally acceptable closure. These tailings facility and dams are shown in Figure 1.

![Figure 1: Red Dog Tailings Facility](image)

The two dams impound tailings and water up the valley of the South Fork of Red Dog Creek to near the saddle of the divide between the watersheds of the South Fork of Red Dog Creek and Bons Creek. Immediately downstream of the tailings main dam is seepage collection system from which seepage water is pumped back to the tailings facility. Neither dam contains a spillway for operations. The tailings main dam will have a spillway around its left abutment for the tailings closure configuration.

The area around the tailings facility that will contribute water to the tailings main dam impoundment at closure consists of the following three distinct catchment areas that total 6.53 square kilometers:

- Main waste stockpile east of the tailings impoundment
- Tailings impoundment which is mostly covered with water
- Arctic tundra natural ground west of the tailings impoundment

Some of the surface runoff that is received by the tailings impoundment is lost to evaporation and seepage. The balance must be retained in the impoundment or discharged. Options for tailing facilities at closure include:

- Zero discharge which may not be feasible or practical under all climatic conditions.
- Physical removal which may not be economically viable, and would just relocate the problem.
- A sinking fund for continued pumping, treatment, and discharge in perpetuity.
Minimize the frequency and magnitude of discharges and ensure that the quality is acceptable.

This paper describes a procedure to calculate the required storage volume that would provide almost zero discharge except in extreme cases. The mine closure will be designed to strive for a “zero-discharge” intent that precludes discharge from the tailings pond into Red Dog Creek and the surrounding environment. The post-closure operations intent is that the current pumping, treatment, and discharge operations are to continue until such time as a “clean pond” is achieved.

Closure design objectives for the Red Dog tailing pond at closure are:

- Passive operation will be maintained once a clean pond status is obtained.
- Hydrologic analysis must be completed using best available data.
- Storage between spillway crest and normal pond surface must be the minimum required to assure zero discharge for all but extremely rare combination of events.
- Design criteria used for calculating storage requirements to assure zero discharge should be based on published guidelines in use.
- Dam and emergency spillway must meet Alaska State dam safety design requirements and design guidelines developed by USACE, USBR, USDA, and other agencies.

This closure design of the Red Dog Mine tailings facility required that hydrologic analyses be completed to provide adequate surcharge capacity in the tailings impoundment, and sufficient spillway capacity to route an inflow design flood (IDF).

It is recognized that an absolutely “zero discharge” impoundment, i.e., with zero discharge under all circumstances and for all conceivable climatic conditions in the future may not be feasible or practical. The best alternative is to minimize the frequency and magnitude of potential discharges from the tailings pond as much as practicable.

**Design Approach**

Most states and federal agencies (USACE and USDA-NRCS) have dam guidelines that assume some flow during specific peak storm events, not “zero discharge”. These do not meet a tailing facility closure intent and do not provide tailings dam closure guidelines. For example, in the following states:

- Nevada - Regulations indicate at closure "the mining company is responsible for breaching the dam or otherwise rendering the dam incapable of impounding any mobile material“.
- Washington - Provides for the regulation of a jurisdictional dam "which contains any substance in combination with sufficient water to exist in a liquid or slurry state at the time of initial containment“ but is silent on the closure of such dams.
- Alaska - For closing tailings dams, the Alaska Department of Natural Resources (ADNR, 2005) Dam Safety and Construction Unit in its Guidelines for Cooperation with the Alaska Dam Safety Program is "interested in the precedent for this activity, both in practice and in regulatory requirements".

Instead of arbitrarily determining a storage volume for tailings dam closures, some guidance is needed. To achieve a “zero-discharge” condition, the Nuclear Regulatory Commission (NRC) Regulatory Guide 3.11 “Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills” (NRC 1977) requires storage of the average annual runoff, a probable maximum flood (PMF) series and a 100-year flood as described below: While uranium industry guidelines are typically more
stringent than those of metal mines, NRC Regulatory Guide 3.11 guideline was considered to be a reasonable approach for the Red Dog tailings facility at closure.

“Either the surcharge capacity of the retention system should be sufficient to store runoffs over its service life or there should be an emergency discharge capacity capable of passing the PMF. The emergency discharge capacity may be obtained by constructing a spillway or by other means. The surcharge capacity should be adequate to store a probable maximum flood series preceded or followed by a 100-year flood, assuming a pool elevation equivalent to the average annual runoff. Probable maximum flood series as used herein comprises two floods: the PMF and the flood equivalent to about 40% of the PMF and about 3 to 5 days prior to the occurrence of the main flood.”

The current pumping and treatment system at the mine is designed to pump out any surface runoff as it accumulates in the tailings impoundment, treat the pumped out water, and discharge it to Red Dog Creek in compliance with water quality discharge regulations. This system will be maintained until the tailings impoundment attains a “clean pond” status. Thus, normally the water surface will be maintained at an elevation of 297.8 meters (El. 297.8), which includes tailings deposited up to El. 297.2 and a water cover of 0.6 meters above the tailings. There will be no exposed tailings beach at closure.

The hydrologic analyses associated with the Red Dog tailings facility closure are conducted in a sequence of three steps as described in the following sections, and as shown on Table 1 below.

### Table 1: Tailings Impoundment Capacity

<table>
<thead>
<tr>
<th>Water Surfaces</th>
<th>Incremental height</th>
<th>Design elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>meter (feet)</td>
<td>meter (feet)</td>
</tr>
<tr>
<td>Design Criteria</td>
<td>Top of Tailings</td>
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<tr>
<td></td>
<td>Water Cover</td>
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<tr>
<td>Surcharge Capacity</td>
<td>Spring Freshet</td>
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<tr>
<td></td>
<td>PMF Series</td>
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<td></td>
<td>100-year Flood</td>
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<td></td>
<td>Spillway Crest</td>
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<td>Spillway Capacity</td>
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<tr>
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<td>Dam Crest</td>
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</tbody>
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### Step 1 - Surcharge Capacity

The pond surcharge capacity starts at the estimated tailings surface level at closure of El. 297.2 plus a 0.6-meter water cover to prevent acid generation (El. 297.8). The surcharge capacity includes capacity for the surface runoff resulting from the average spring freshet and May precipitation, a PMF series and a 100-year flood in the catchment area of the tailings pond.

For a conservative estimation of the surcharge capacity for the tailings pond, it is assumed that the pumping, treatment, and discharge system breaks down in the critical “freshet” month of May. Thus, the average spring freshet from the snowfall and rainfall during the months of November to April and
the runoff from the month of May will be stored within the surcharge capacity of the tailings pond. Usually, the system remains idle during the winter months of November to April.

In addition, it is hypothesized that a PMP event also occurs in the same month of May. Although the persistence of a long-duration PMP on a relatively small catchment of 6.53 square kilometers is a very low-probability event, it is conservatively assumed that the PMP has a relatively long duration of 24 hours. Further, it is hypothesized that the PMP event is preceded or succeeded by a 40% PMP and also a 100-year precipitation event of the same relatively long duration of 24 hours in the same month (in other words - 1.4 x PMP plus 100-year precipitation). The total storage capacity required to store the runoff resulting from these successive extreme events is equivalent to the storage capacity specified by the NRC to achieve zero discharge conditions from uranium mill tailings impoundments (NRC, 1977).

A portion of the precipitation depths during the above successive events will be lost in interception, evapotranspiration, infiltration, and depression storage in the watershed before reaching the tailings impoundment as surface runoff. To be conservative, it is assumed that these losses will be as small as on impervious areas and water surfaces.

**Step 2 - Spillway Capacity**

The spillway discharge capacity will be above the surcharge storage capacity, and will start at the spillway crest elevation (Table 1). It will consist of the height produced by routing an IDF of a 0.5 PMF through the spillway and the freeboard required to contain wind setup and wave runup associated with coincident wind speeds. The spillway can also pass a full PMF without the maximum water surface elevation rising above the dam crest.

Since a spillway is provided above a surcharge capacity, the provision of additional freeboard for wind wave activity below the spillway crest is not considered necessary. So far as safety against dam overtopping is concerned, a freeboard of 0.8 meters will be available between the dam crest at El. 300.5 and top of surcharge capacity at El. 299.8. The potential for wind wave splashes over the spillway crest, El. 299.8, when the impoundment is full has a very low probability and short duration.

The provision of permanent storage capacity for such a temporal activity over and above the conservatively estimated surcharge capacity appears to be overly conservative. In fact, the purpose of the spillway is to discharge such occasional overflows such as wind wave splashes and rare coincidence of a PMP or less intense precipitation events with the combined event of a PMF series plus 100-year flood.

The spillway is provided to add a degree of redundancy and conservatism and is not expected to discharge any water from the impoundment except in extreme events of very low probability.

In the unlikely event of any outflow through the spillway, only the top layer of water above the spillway crest (El. 299.8) would be discharged through the spillway. This top layer of water will be separated from the tailings by about a 2.6 meters (El. 299.8 – El. 297.2) thick water cover and should be relatively clean. Thus, even under this almost improbable situation, there may be no significant impact on the water quality of Red Dog Creek.

**Step 3 - Freeboard**

Freeboard against wind wave activity and potential dam overtopping is provided above the maximum water surface elevation estimated for the case when a one half PMF is routed through the spillway. The adopted dam design freeboard includes wind setup and wave runup on the slope of the sub-surface beach, which is assumed to be 1 vertical to 100 horizontal (1:100), due to wind wave activity coincident with a one half PMF flow through the emergency spillway.
The spillway may become operative only in the unlikely situation when the entire surcharge capacity has been filled up due to a highly unlikely sequence of extreme events, such as a PMF series plus 100-year flood, and a pump breakdown in conjunction with spring freshet in the critical month of May. The probability of an additional full PMF discharge through the spillway concurrent with the above is extremely low.

Therefore, the dam crest was set to pass the full PMF without the water surface rising above it. A parapet berm will be required at the upstream edge of the dam crest as protection against wave overtopping during the unlikely event of a full PMF. The USBR, 1992, defines the PMF as having a relative return period of 1 in 10,000 years. The parapet berm would be built of coarse rockfill or riprap, and is considered adequate for this purpose and avoids the need to build a higher dam.

In addition to these design steps, the actual spillway will be located along the left abutment hillside above the dam and not in the dam embankment as shown on Figure 2. The design will be determined on the basis of the site hydrology and hydraulics, and soil and rock conditions along the alignment. The current design concept includes the spillway entrance, broad-crested spillway, outlet channel, erosion protection and stilling basin for long-term operability and creek protection.

**Methods and Results**

**Surcharge Capacity**

This section describes the method of estimating surcharge capacity to be provided in the tailings facility below the spillway crest at closure. The surcharge capacity includes three components:

- Spring freshet
- Probable maximum flood series
- 100-year flood

**Spring freshet**

Established dam operations practices and FEMA guidelines (FEMA, 2004) recommend the consideration of possible spillway and outlet works malfunctions when determining outflows and storage for sizing spillways. It was assumed that the Red Dog water treatment plant could break down for one month and prevent discharge from the tailings facility.

May was conservatively chosen as that month because it is the largest runoff month. The surface runoff in May includes the spring freshet which is precipitation accumulated from November to April, and the precipitation in May itself.

The surcharge capacity contribution from spring freshet was estimated using the following values and sources of data:
Figure 2: Red Dog Mine Tailings Facility Plan View
Average Red Dog Mine precipitation data from 1992 to 2007 for May

Catchment contributing to the tailings facility calculated using a mine site topographic map based on photography taken in 2007 and produced at a scale of 1 centimeter to 24.0-meter

Catchment curve number (CN) conservatively estimated to be 98 as specified in NRCS guidance on hydrologic soil-cover complexes: “Impervious and water surfaces, which are not listed, are always assigned a CN of 98” (NRCS, 2004). (Theoretically, the CN varies between 0 and 100. A CN of 100 represents that all precipitation on the catchment becomes runoff.)

A stage-storage table for the tailings facility was developed off mine topographic maps. The volume capacity at each stage was then determined by multiplying the average area of the preceding and current contour stage surface areas by the 0.3-meter depth between the stages.

Using the values above, the average May runoff into the tailings facility, including the spring freshet, was determined from the total average May runoff minus average evaporation and seepage losses during May. The resulting runoff was equivalent to a pond water depth of 0.42 meters above the tailings water surface level of El. 297.8. This would raise the pond stage water level to El. 298.2.

**Probable maximum flood series**

The PMF series was calculated by estimating a PMP event from U.S. Weather Bureau data and local precipitation data at Red Dog Mine and Kotzebue, AK. A catchment area of 6.53 square kilometers and a CN of 98 were used to determine the runoff from the PMP to enter the pond as the PMF. The PMF was then multiplied by 40% to obtain the PMF series prescribed in NRC 1977.

The occurrence of a sustained PMP for a relatively long duration of time, such as greater than 6 hours, over a relatively small drainage area of 6.53 square kilometers is a very low probability event. Therefore, to be conservative, a PMP of 24-hour duration was adopted.

The PMP is defined by the National Oceanic & Atmospheric Administration (NOAA) as the theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year (NOAA, 1994).

One of the most commonly used methods to estimate PMP for a given drainage basin is to follow the procedures and charts in the NOAA Hydrometeorological Report or Technical Paper for the region where the basin is located (National Research Council, 1985; Bureau of Reclamation, 1987; Ponce, 1994). These procedures and charts reduce the need for detailed site-specific analyses for storm transposition, moisture maximization and orographic effects for each site.

The U.S. Weather Bureau document that is applicable to the Red Dog mine is Technical Paper No. 47 (TP-47) (Weather Bureau, 1963). TP-47 includes a generalized chart (Figure 2-12) for 24-hour PMP in Alaska. The 24-hour PMP for the Red Dog Mine site interpolated from this chart is approximately 15.0 centimeters. However, as discussed below, it is prudent to adjust this value to fit site conditions.

The gage density that was used to develop the charts in TP-47 was one gage per 8,300 square kilometers. The average density in the United States is one gage per 650 square kilometers. In particular, the gage density north of the 650 latitude in Alaska was 21,500 square kilometers per gage. This unusually sparse gage density, relatively short periods of records, rugged topography, and extreme arctic climatic regimes made it difficult to make an accurate estimation of the PMP for this region.

Consequently, the results in TP-47 are deemed to have a lower degree of accuracy than those in NOAA reports for other parts of the United States. In particular, the isopluvials in Figure 2-12 indicate a lower PMP at Red Dog (in the mountains north of Kotzebue) than at Kotzebue. In contrast, the observed
precipitation depths at the mine have been greater than at Kotzebue. It appears that the orographic and elevation effects affecting the precipitation at the mine are not adequately accounted for in Figure 2-12.

One station from which precipitation data was used in developing the TP-47 charts is in Kotzebue. It is concluded that the estimated PMP at Kotzebue is based on analysis of site-specific data and is reasonable. A procedure suggested to estimate PMP for locations similar to Red Dog includes adjusting the PMP for the nearest nonorographic location (Kotzebue) for topographic effects using comparison of extreme rainfalls of various categories at the two locations (National Research Council, 1985).

Long-term precipitation data are available at the Weather Bureau gage at Kotzebue Airport (Latitude 66°2’ N, Longitude 162°38’W, El. 10) (National Climatic Data Center, 2008). Also, daily precipitation values are available for approximately 16 years (1992 to 2007) for the Red Dog gage.

There is usually a difference in the observed daily (observational-day) precipitation and precipitation measured during a sequential period of 24 hours (or 1440-minutes) containing the maximum amounts. Based on the reported average ratio between the two values, the 24-hour precipitation depth was assumed to be 1.13 times the corresponding daily value at each of the two stations (Weather Bureau, 1961).

Concurrent precipitation depths at the gages at Kotzebue and Red Dog Mine were compared to develop a relationship between the two stations. The resulting multiplying factor is deemed to represent the orographic and meteorological effects applicable to the Red Dog Mine area. The ratio of the mean of daily maximum values observed in each year during the period of concurrent data (1992 to 2007) for the Red Dog Mine and Kotzebue gages is 1.7.

From Figure 2-12, the 24-hour point PMP for Kotzebue is approximately 19.8 centimeters. The PMP for Kotzebue and the gage ratio between Red Dog Mine and Kotzebue as a multiplying factor was then used to estimate the 24-hour PMP at Red Dog Mine. Thus, the estimated 24-hour PMP at Red Dog is 33.7 centimeters (equal to 1.7 x 19.8 centimeters). Several approximate methods were used to verify the reasonableness of the estimated PMP.

The same catchment area (6.53 square kilometers) and CN (98) that were used for the May runoff calculations were used along with the calculated PMP to determine the PMF series contribution to the tailings impoundment storage depth of 1.30 meters above the water surface level at El. 298.20 that was obtained after storing the runoff during the spring freshet. The storage of this volume in the tailings impoundment raises the water level to El. 299.50.

**100-Year flood**

The 100-year flood contribution to the pond surcharge capacity was determined using the same methodology as used in determining the PMF. The 24-hour, 100-year precipitation for Kotzebue was determined from Figure 3-59 of Technical Paper 47 (Weather Bureau, 1963) to be 6.4 centimeters. Adjusting this value by the previously used Red Dog Mine to Kotzebue site ratio of 1.7, yields a 24-hour, 100-year precipitation of 10.80 centimeters.

The same catchment area (6.53 square kilometers) and CN (98) which were used for the May runoff calculations were used along with the calculated 24-hour, 100-year precipitation to determine the 100-year flood contribution to the pond storage depth of 0.28 meters above the water surface level of El. 299.50 that was computed after adding the PMF series. The storage of this volume in the tailings impoundment raises the water level to El. 299.78.
Spillway Capacity

The spillway capacity was developed on the basis of routed inflow design flood and freeboard criteria. The Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) (USACE, 2001) model was used to estimate the peak flow through the spillway and water elevation in the tailings facility when routing the IDF and the extreme event of a PMF. The HEC-HMS model input parameters that were used in the modeling include the catchment area and CN described previously, as well as:

- Inflow design flood
- Lag time
- Stage storage discharge curve.

The results of the HEC-HMS model for routing the IDF through the spillway were a peak flow and depth of flow of 4.4 cubic meters per second and 0.4 meters, respectively. It was determined that 0.07 meters of water height will be required in the tailings facility to provide the head needed to overcome friction and convergence losses from pushing water up the inlet channel to the spillway outlet. The required head was determined using Hydrologic Engineering Center-River Analysis System (HEC-RAS) software (USACE, 2004). The maximum water surface level in the tailings facility during the half PMF event is estimated to be El. 300.2, 0.43 meters above the spillway crest at El. 299.8.

A full PMF, rather than one half PMF, was routed through the spillway as an extreme-case condition check for spillway capacity. The peak flow and depth through the spillway that would develop from routing a PMF were calculated to be 11.5 cubic meters per second and 0.7 meters, respectively.

An additional 0.09 meters of water height will be required in the tailings impoundment to provide the head needed to overcome frictional and convergence losses from pushing the water up the inlet channel to the spillway outlet. The required head was determined using HEC-RAS software. Therefore, the maximum water surface level in the tailings impoundment dam during the full PMF event is estimated to be El. 300.6, which is 0.76 meters above the spillway crest at El. 299.8, and just over 0.3 meters more than that was calculated for one half of the PMF.

Freeboard

For the preliminary spillway design, the required freeboard on top of the IDF (one half PMF) was calculated in order to prevent the tailings main dam from being overtopped. This required freeboard must accommodate the wind setup and wave runup. Also, the required freeboard on top of a PMF was calculated to size whatever parapet berm might be needed to prevent overtopping of the dam as a result of wind-generated waves in a very extreme precipitation event. The parapet berm is assumed to be adequate for this purpose, and avoids the need to build a higher dam that is not necessary.

Wind setup

Wind setup is the piling up of water on the leeward end of a body of water due to the horizontal stress that the wind exerts on water as it blows across the water surface. This stress causes the piling up of water on the leeward end of body of water, which in this case was assumed to be the north end of the tailings impoundment at the tailings main dam and spillway inlet area. The parameters used to calculate wind setup are listed below and detailed in the following subsections.

- Fetch length - The fetch length was measured as the longest “straight-line” distance (USACE, 2006) between the tailings back dam and 34 meters upstream of the tailings main dam where the still-water pond level reaches at an El. 300.2 from routing the IDF through the spillway. The fetch length was calculated to be 2.65 kilometers.
Water depth – The design water depth was calculated to be 3.0 meters measured from the maximum water surface level in the tailings impoundment based on the HEC-HMS model of the IDF routed through the spillway, minus the assumed average tailings elevation (El. 300.2 – El. 297.2 = 3.0 meters).

Design wind velocity - The design wind velocity was determined using USACE (2003), NRC (American Nuclear Society, 1992) and NRCS (1983) guidance. The calculations from these three techniques produce similar design wind velocities. A design wind velocity of 32.2 meters per second was selected as a conservative calculation of the design wind velocity.

The wind setup was calculated to be 0.19 meters for the IDF of one half of the PMF, and 0.17 meters for the extreme event of a full PMF. This wind setup was calculated with the parameters above using Army Corp of Engineer guidance (USACE, 1997). The design wind velocity was used to calculate the wind setup occurring at the time of wave runup. Wind setup is normally calculated using average wind velocities. However, when the wind setup is being added to wave runup for a cumulative effect, the same wind velocity is assumed in both calculations.

Wave Runup

Wave runup is the movement of water up a structure or beach upon the breaking of a wave. Wave runup for the routing of the IDF thought the spillway was estimated using the USACE Coastal Engineering Manual (2006). The wave runup was calculated to be 0.15 meters for the waves against the beach assuming a beach slope of one percent down away from the dam crest to the berm that will confine the beach 183 meters away from the dam.

In the extreme event of a PMF, wave runup will occur against a parapet berm that is constructed of coarse rock or riprap along the upstream side of the tailings main dam. USBR guidance (1992) was used for calculating wave run-up to be 0.80 meters.

The total freeboard for the IDF, based on the wind setup and wave runup, required for the preliminary spillway design is estimated to be 0.34 meters, which is determined by adding the wind setup estimate of 0.19 meters and the wave runup estimate of 0.15 meters and then rounding off.

Conclusions

The spillway and dam crest elevations are estimated to be El. 299.8 and El. 300.5, respectively, for the tailings impoundment at closure. The surcharge capacity and spillway capacity, to include freeboard, estimated to attain these elevations are summarized in Table 1.

The design concepts used in the step-by-step process of estimating the surcharge and spillway capacity required for closure of the tailings impoundment at Red Dog Mine provide a straightforward, well-referenced methodology to follow in order to minimize discharges from abandoned solid waste impoundments. The conservative NRC guidelines appear to provide adequate surcharge capacity, especially with an accompanying emergency spillway.

The hydrologic closure design of the Red Dog tailings facility offers answers to design challenges for waste impoundments in remote regions, where site conditions and atmospheric data are often limited.

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