Staged emergency spillway development – design considerations

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ABSTRACT: Under most circumstances, spillway structures are required for the safe operation of a dam, helping to control the release of excess water within the impoundment to a location downstream. Where spillway facilities exist, it is essential that they are capable of operating throughout their design life and within prescribed regulatory requirements. This condition becomes more challenging when an emergency spillway needs to be incorporated into the design of a tailings storage facility (TSF). TSFs are typically designed for the final arrangement anticipated at mine closure. In order to reduce mine operating capital costs, TSFs are often constructed in staged lifts as dictated by tailings production estimates. Consideration for the spillway is required with each lift. Several factors influence the dam and spillway geometry including supernatant pond volumes, climatic conditions, tailings production rates, volumetrics of the impoundment, spillway location, geotechnical considerations, mine closure criteria. This paper will explore the key considerations for the development of a TSF emergency spillway. The spillway development at the Phu Kham Copper-Gold Operation (operated by Phu Bia Mining Limited) located in the Lao People's Democratic Republic will be used to illustrate these considerations.

RÉSUMÉ : Dans la plupart des cas, un évacuateur de crue est nécessaire à l'exploitation sécuritaire d'un barrage, il permet l'évacuation des eaux en excès de la retenue vers un emplacement en aval. L'évacuateur de crue doit être en mesure d'être exploiter durant sa durée de vie utile et dans le respect des exigences réglementaires prescrites. Cette condition se complique lorsque l'évacuateur de crue d'urgence doit être intégré à la conception d'un parc à résidus miniers. Les digues de retenues de résidus miniers sont généralement conçues en fonction l'arrangement final prévu à la fermeture de la mine. Afin de réduire les coûts d'exploitation de la mine, les parcs à résidus miniers sont souvent construits en étapes sur plusieurs années, selon les estimations de la production de résidus miniers. À chaque étape de rehaussement de crête de la digue du parc à résidus minier, il convient de prendre en compte l'évacuateur de crue. Plusieurs facteurs influencent la géométrie de la digue et de l'évacuateur de crue, tels que: volumes de retenue de surnageant, les conditions climatiques, les taux de production de résidus miniers, la volumétrie du bassin de retenue, l'emplacement de l'évacuateur, les considérations géotechniques, les critères de fermeture des installations, etc. Les considérations relatives à l'aménagement d'un évacuateur de crues d'urgence pour un parc à résidus miniers y sont présentées. Le développement de l'évacuateur de crue à la mine de cuivre et or Phu Kham (exploitée par Phu Bia Mining Limited) située en République démocratique populaire lao servira à illustrer ces considérations.

1 INTRODUCTION

Spillways ensure that excess water accumulating in a Tailings Storage Facility (TSF) is safely released. This is essential for safe operation of the facility.

In some cases a spillway may not be required if the TSF is designed for full containment of the design rainfall event, such as a wet season water storage. A detailed assessment is required to understand the costs and benefits (or risks) of designing a TSF for flood storage or flood release with a spillway. For a large TSF, an emergency spillway is usually the lowest risk and lowest cost option in wetter climates, whereas full containment may be a better option where arid conditions prevail.

1.1 *Spillway Planning*

Typically, tailings dams are raised annually in staged lifts to accommodate the operating phases of a mine and containment structure requirements. Planning for a tailings facility's emergency spillway should start during its conceptual design. Conceptual planning of a TSF includes an initial assessment of the required tailing containment volume, tailings production rates, assessment of other materials such as waste rock that could reduce the tailings containment volume, methods and management of surface water around a TSF and water storage allowances during the operating phase. Emergency release of excess water must take into account the regulatory requirements, operating licenses, permits of a TSF and evaluation of the environmental consequences and impacts related to water release during a flood event.

During the conceptual design phase, further assessments will be made with respect to the timing for implementing the emergency spillway. Staging of spillway construction will also be considered at this stage to ensure the preferred spillway concept can be feasibly constructed during the TSF raises during the operating phase. In some cases during the early years of tailings dam construction, full containment of the wet season water storage and extreme storm events may be viable, helping to push capital expenditure related to the emergency spillway into future years of construction. Understanding at what time during the development of a TSF an emergency spillway will be cost effective will dictate the location, type and size of the spillway structure. A TSF's design must also facilitate closure and post-closure strategies. A mine owner and operator's post-closure target should ensure the closed facility does not require ongoing maintenance, the lands can be returned to the original land use and the owner/operator be released of responsibility.

2 PHU KHAM EMERGENCY SPILLWAY DEVELOPMENT

The Phu Kham Copper-Gold Operation (Phu Kham) is located in Lao People's Democratic Republic (Lao PDR) approximately 140 kilometres north of the capital city, Vientiane. Phu Kham is operated by Phu Bia Mining Limited (PBM), who also operate the nearby Ban Houayxai Gold-Silver Operation. Both mines are located in highly weathered mountainous jungle terrain and exposed to the June to September annual monsoon season. Brisbane-based copper and gold producer, PanAust Limited (PanAust) own a 90% interest in PBM; the Government of Laos own the remaining 10%.

Phu Kham commenced commercial production in 2008 following the construction of the stage 1A zoned earthfill embankment. The embankment has been raised annually to its current height of over 160 m and is expected to be completed in 2021 at a height of approximately 180 m. The requirements and strategy for emergency spillway development has evolved at Phu Kham's TSF to match with production requirements, embankment design and closure plans. This paper will provide a summary of the challenges related to the design and implementation of the TSF emergency spillway in relation to these requirements.

Figure 1. Phu Kham Emergency Spillway – Photo of Stage 2 spillway raise

2.1 *Design Basis Criteria*

The TSF at Phu Kham was designed to standards outlined in the Australian National Committee on Large Dams (ANCOLD) Guidelines on Tailings Dams (ANCOLD, 2012a) with regard to dam planning, design and construction. Consequence Categories for Dams guidelines (ANCOLD, 2012b) were selected as the basis for determining the dam consequence classification and subsequently determining the design flood annual exceedance probability (AEP) and total freeboard allowances. The Phu Kham TSF is designed for full containment of a 1:250 year wet season water volume plus the 1:100 year 24-hour rainfall event prior to the emergency spillway operating. The spillway and outlet works are designed to manage floods up to and including the probable maximum flood (PMF). A summary of the spillway design basis criteria is shown in Table 1.

Table 1. Emergency spillway design criteria

Parameter	Value
Consequence category	High B
Design flood AEP	72-hour PMF of 203 m^3/s
Minimum wet season storage allowance	1:250 year AEP
Freeboard	1.0 m

2.1.1 *Full containment during early phase of mine operation*

The Phu Kham tailings facility was initially designed as a non-release facility and operated for full containment of the design flood. A detailed assessment was completed to assess the costs of developing an emergency spillway versus raising the facility for full containment of the design flood. It was determined that at the early stages of the operation phase, staged dam construction for full flood containment was more economical than the construction of an emergency spillway following the staged dam construction.

2.1.2 *Initial life of mine emergency spillway*

During the 2012/2013 embankment construction season, the assessment of the cost of spillway development versus dam construction for full containment of the design flood, indicated that an emergency spillway would be more economical than the construction for full flood containment. The initial spillway was designed to discharge only a half PMF until 2015 before the spillway design flow was increased to pass the critical full PMF. The emergency spillway was developed on the eastern abutment of the main TSF embankment dam, consisting of a riprap-lined channel located on the dam's downstream slopes and designed to safely discharge flows away from the embankment toe. As the embankment dam would be raised during the operation phases, the emergency spillway would be removed and reconstructed.

During the 2014/2015 construction season, as dam construction encroached on the eastern abutment, the emergency spillway was integrated into the embankment dam and the discharge point was shifted further to the east to ensure the embankment dam was not impacted should the spillway discharge.

The 2015/2016 embankment construction identified that significant earthworks would be required to develop a spillway outlet channel that would safely accommodate spillway discharges away from the embankment toe. Relocation of the emergency spillway was proposed.

The TSF arrangement and location of the initial emergency spillway (2015/2016 arrangement) is shown in Figure 2.

2.1.3 *Relocation of the emergency spillway*

2.1.3.1 Assessment of risks, costs and benefits

To determine the most appropriate location for the emergency spillway, a detailed assessment and evaluation of spillway alternatives using the following framework was completed:

- Identify and develop a conceptual design of spillway arrangements that would allow for the staged lift construction of the spillway invert to accommodate the operating stages of the TSF and containment requirements for the remaining life of mine.
- Identify spillway locations where flood discharge would have limited impacts on local stakeholders (farmers, agriculture), the surrounding environment (loss of tailings through re-suspension during high spillway flows, natural erosion and sedimentation), the TSF structures and other existing mine infrastructure while reducing construction complexity and congestion of annual TSF construction programs between the embankment wall and spillway(s).
- Identify the geotechnical conditions for each proposed spillway location.
- Analyse the risks and benefits of each spillway concept.
- Estimate the development costs of each spillway concept.

In addition to evaluating the relocation of the emergency spillway, the assessment also considered upgrades to the initial emergency spillway for the Operation's remaining mine life, as well as full containment of the PMF with staged embankment construction. Evaluations concluded the cost and risks of these options were unacceptable and were therefore not considered further. With respect to maintaining the initial emergency spillway, risks included the potential for overtopping of the spillway resulting in uncontrolled flows over the earthfill embankment, and erosion at the spillway outlet leading to environmental damage in the downstream catchment. Mitigating these risks would result in significant increased costs to construct the facility. With respect to full containment of the PMF additional embankment dam construction costs in order to achieve the appropriate storage would be much more than the development cost for a new spillway.

Relocation of the spillway to an alternative location was focused along the northern end of the western rim of the TSF. This location was selected for several reasons including: close proximity to known bedrock exposures, favorable site topography with low elevation drop from spillway invert to the natural stream channel below, and the natural narrowing of the ridgeline that would result in reduced excavation volumes.

Additional geotechnical site investigations were conducted in this area during the concept development to identify the foundation conditions and depth of the bedrock. Bedrock, or competent rock foundations, were preferred in order to minimise risks associated with erosion potential during spillway operation, seepage below the spillway structure, and foundation bearing capacity, allowing more flexibility for spillway and outlet works arrangement. Bedrock at all locations investigated was found to be predominantly siltstone and much deeper than anticipated with foundation zones varying from high to moderately weathered siltstone and sandstone.

During the evaluations of alternatives, rubble masonry concrete, roller compacted concrete (RCC) or concrete dam structures were identified as lower risk structures due to their robustness. Rigid dams alternatives were not advanced since weathered bedrock foundations were identified to have insufficient strength to support a high rigid structure without significant costly foundation treatment.

Potential failure modes analysis of the preferred spillway alternatives were performed following a quantitative failure mode and effects analysis by a multi-disciplinary team composed of design engineers, the engineer of record, representatives of the Owner, mine operation managers and construction managers. The risk analysis framework was developed by PanAust and included evaluation of health and safety, environmental, social, security, regulatory, production and financial consequences. The outcome of the risk analysis helped identify the lowest consequence option and key design requirements to manage the risks of the preferred spillway alternative.

The detailed assessment and evaluation of alternatives identified that the preferred spillway arrangement is a staged lift constructed surface spillway over a zoned earthfill embankment. This assessment also concluded that a closure spillway placed directly on native ground would present the lowest risk alternative for mine closure.

2.1.3.2 Emergency spillway criteria

The relocated emergency spillway was proposed to be developed in five stages throughout the remaining life of mine. Prior to the detailed design phase, a feasibility study was completed for the preferred spillway arrangement in order to further assess the costs and refine the conceptual design. The staging summarised in Table 2 was proposed for the construction of the emergency spillway. The location of the relocated emergency spillway is shown on Figure 2.

Table 2. Emergency spillway staging

Stage	Construction season	Description
1	2016/2017	Excavate to spillway invert Low gradient riprap lined spillway
2	2017/2018	Zoned Earthfill embankment Low gradient riprap lined approach channel Reinforced concrete chute spillway Low gradient riprap lined outlet channel
3	2018/2019	Remove approach channel riprap and top section of chute and raise to new invert Raise zoned earthfill embankment crest Reinstate approach channel riprap
4	2019/2020	Remove approach channel riprap and top section of chute and raise to new invert Raise zoned earthfill embankment crest Reinstate approach channel riprap
5	2020/2021	Remove approach channel riprap Raise zoned earthfill embankment crest to closure elevation
6	2020/2021	Construct closure spillway

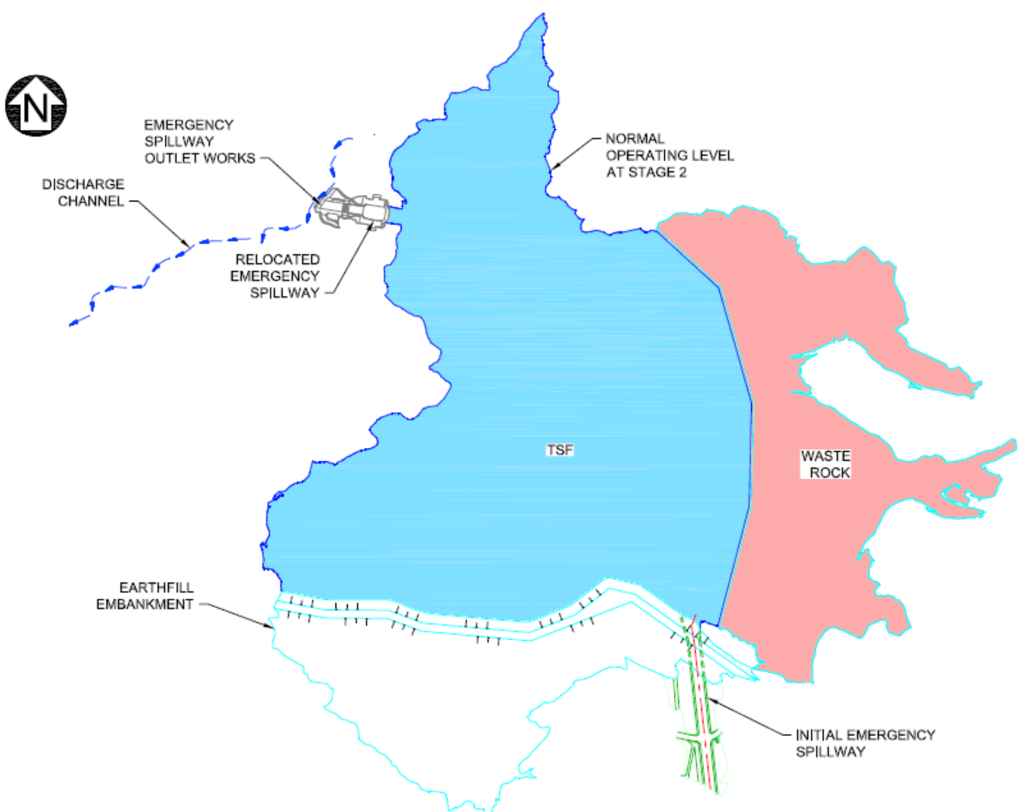

Figure 2. Phu Kham TSF and emergency spillway arrangement

2.2 *Closure plan*

The mine closure plan considers that all TSF installations including the spillway embankment will remain in place after closure. The closure concept for the relocated emergency spillway is that the spillway embankment will act as a saddle dam to retain tailings within the TSF post mine closure. The closure plan also considers the changes in site water management as the facility is decommissioned.

During construction of stage 5, the crest of the spillway embankment will be raised to match the specified closure crest elevation of the TSF. The concrete emergency spillway and outlet works developed during stages 1 to 4 will be decommissioned. Prior to the construction of stage 5, a separate purpose built closure spillway will be developed to the north of the emergency spillway to accommodate post mine closure flow conditions.

3 Design for staged spillway development

The emergency spillway structure consists of a 21 m high earthfill dam constructed in staged lifts, an uncontrolled concrete chute spillway and a hydraulic jump stilling basin. The emergency spillway is sized to pass the critical PMF without overtopping of the TSF. The spillway arrangement includes an entrance channel and chute control structure located at the crest of the engineered earthfill embankment. The approach channel and chute control structure will be raised following each staged lift construction of the spillway embankment with a new segment of chute spillway being constructed for each lift. The spillway chute is located on the final dam fill slopes and the hydraulic jump stilling basin, similar in geometry to a USBR type III stilling basin is located at the toe of the embankment. Freeboard within the hydraulic jump stilling basin outlet channel is provided to prevent discharge along the toe of the spillway embankment.

3.1 *Spillway design considerations*

During the detailed design phase of the Phu Kham emergency spillway, considerations were made to meet the following criteria:

- The spillway size had to pass the critical PMF.
- Staged lift construction needed to satisfy the operating stages of the mine.
- The spillway embankment must satisfy the construction requirements and the embankment elevation of the TSF at closure.
- At stage 5, the emergency spillway needed to be converted into a saddle dam once the stage 6 closure spillway was operational.

Seepage, embankment stability and settlement analysis were completed for the operation phase of the embankment stages 1 to 4 and for the saddle dam as defined by the closure plan (stage 5) in order to ensure that the structures satisfy the entire life cycle of the facility.

The hydraulic design of the emergency spillway arrangement at all stages described in Table 2 was completed during the initial phase of the detailed design in order to ensure the spillway and outlet works could accommodate all stages of the facility. Reservoir flood routing modelling was completed for the emergency spillway at each stage described in Table 2 with estimated reservoir elevation storage data. It is anticipated that the reservoir flood routing will be revised with updated elevation storage data as the tailings deposition evolves throughout the operation phase. The critical PMF was defined as the stage 1 flood event, assuming a linear elevation storage relationship for stages 2 to 4, the PMF events will be incrementally smaller as a function of the increased reservoir storage capacity.

The hydraulic performance and energy dissipation of the hydraulic-jump stilling basin were investigated following published North American guidelines (A.J. Peterka, 1984, USACE, 1992) and modeled with computational fluid dynamic CFD software.

3.2 *Staged raise construction of spillway*

The construction of the staged emergency spillway crest consists of the removal of a portion of the works completed during the previous stage, and construction of new spillway elements including earthfill embankment and chute spillway structures, as the height of the earthfill embankment is increased. This will satisfy the containment requirements of each of the TSF construction stages. Figure 3 illustrates the staged development of the Phu Kham life of mine emergency spillway as proposed during the planning stages.

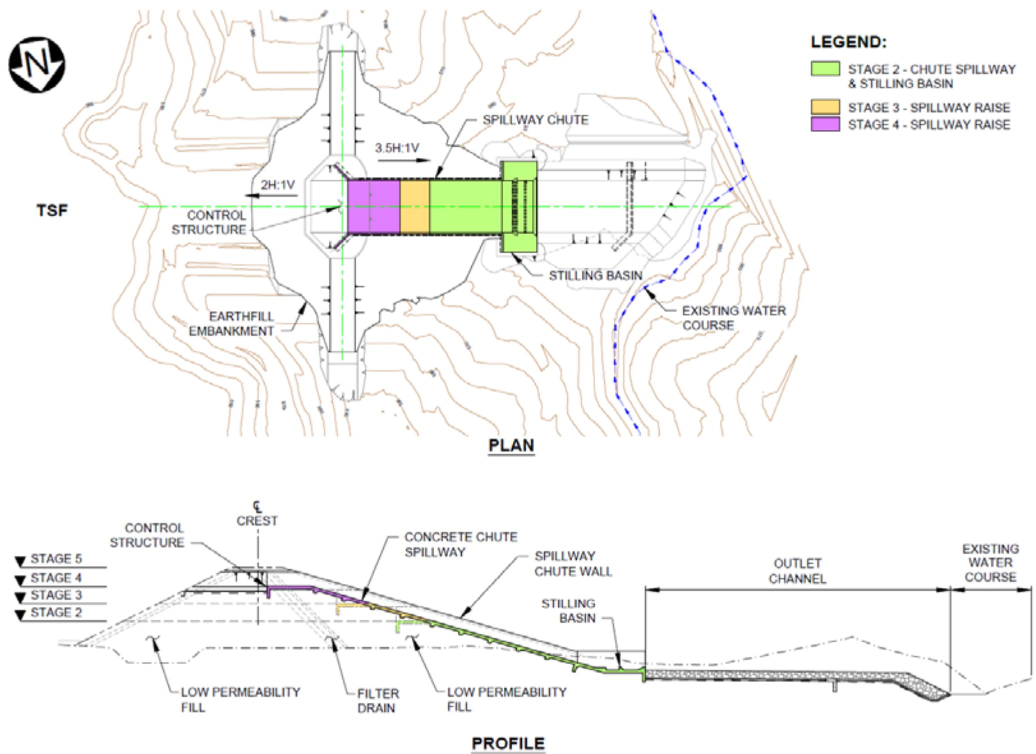

Figure 3. Phu Kham emergency spillway stages

During stage 2, riprap placed during stage 1 is partially removed to allow for embankment fill placement and concrete spillway construction (control, chute and energy dissipator). During stages 3 and 4, entrance channel riprap and chute control sections are removed, embankment fill is placed to match main embankment elevations, entrance channel riprap is replaced and chute and control structures are constructed to achieve the required spillway invert elevation. Stage 5 construction requires removal of the approach channel riprap and earthfill placement to achieve the closure embankment elevation. Riprap used for the entrance channel is re-used during all stages of construction. The concrete chute control section is removed and disposed of outside the spillway embankment. Each staged lift typically requires an additional section of chute structure and a new concrete chute control section. All concrete joints are designed as contraction joints and include un-bonded surfaces separating adjacent concrete placements, formed load transfer concrete key joints and PVC waterstop to mitigate adverse hydraulic conditions.

This method of staged spillway lift construction was considered to allow conventional construction methods and for the emergency spillway geometry to be adaptable should the operation stages of the mine change throughout mine life.

4 Conclusion

The Phu Kham TSF emergency spillway was developed following a detailed assessment of risks, costs and benefits. Failure modes risk analysis allowed PanAust to make a risk-informed development decision, mitigate and manage risks and minimize the consequences of emergency flood discharge while meeting the TSF operational requirements.

A staged lift constructed surface emergency spillway constructed over an earthfill embankment with adequate overtopping protection was found to be economical and feasible through detailed engineering and good understanding of the operating stages of the mine. This alternative also provided sufficient flexibility for changes in mine operational conditions.

5 References

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