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Numerical analysis and geophysical monitoring for stability assessment of the Northwest tailings dam at Westwood Mine

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ABSTRACT

The Westwood Mine aims to reuse the tailings storage facility #1 (TSF #1) for solid waste storage, but, downstream of the Northwest dike is considered critical in terms of stability. This paper uses numerical modeling along with geophysical monitoring for assessing the Northwest dike stability during the restoration phase. The impact of waste rock deposition in the upstream TSF #1 is considered. The geophysical monitoring is based on electrical resistivity methods and was used to investigate the internal structure of the dike embankment in different deposition stages. The numerical simulations were performed with SLOPE/W code. The results show a factor of safety well above the minimum recommended value of 1.5. Geophysical monitoring revealed a vertical variation in the electrical resistivity across the dike, which indicates a multilayer structure of the embankment. Without any current in situ data, the geophysical monitoring helped estimating the nature of the materials used and the internal structure of the embankment. These interpretations were validated by geological observation of geotechnical log of the embankment. Based on this study, it is recommended that the water polishing pond be partly filled before waste rock is deposited in TSF #1. In addition, to ensure the stability of the dike, the piezometric head monitoring prior to and during waste rock deposition is recommended.

1. Introduction

The mining industry is the backbone of the economy of any natural resource country with active mines, but mining also generates large quantities of solid wastes such as tailings and waste rock that must be properly confined either in tailings storage facility (TSF) or waste rock dumps, respectively. The reason being that the exposure of these solid wastes to atmospheric conditions could result in environmental pollution by acid mine drainage or contaminated neutral drainage. When underground mining methods require that the stopes are artificially supported to allow full ore recovery, backfilling is an effective way of partial solid waste management. In a TSF, mine tailings are surrounded by the embankment dikes that must be monitored to prevent spillage of slurry tailings. However, these dikes can sometimes yield to different types of hazard and spillage of tailings pulp, which could generate extensive damage and major environmental impacts. Fig. 1 shows a break in the dam of Mount Polley (Canada) mine tailings impoundment with over 24 million m^3 of tailings spilled [1]. Damage along with the death of 19 people was also reported due to the bursting of tailings dam in Mariana, Brazil in 2015 [2]. The socioeconomic impact of disruptions in the world with the loss of life and the impact on public health increased between 2000 and 2010. About 76% of the incidents worldwide are related to upstream construction methods; 51% of incidents (breakdowns and accidents) identified by ICOLD are due to slope instability dikes following excessive stress in the foundation soil, excessive stress in the embankment of the dam and inadequate control of water pressure [3–6].

The causes of dam breakage are multiple. Apart from construction problems, poor maintenance or unusual weather is as cited by Azam and Li [7]. Other vulnerability may also be the cause of excess pore pressure accumulation due to rapid rising of the dam. Pore pressure (especially in muddy areas) will reduce the effective stresses and the shear strength of tailings [8,9]. Static and seismic liquefaction is also considered as common causes of levees particularly those enhanced by the upstream method [10,11]. As the break is a physical process (mechanical, hydraulic), in general, the breakdown for embankments occurs according to one of four classical mechanisms: external erosion, internal erosion, external instability and liquefaction [12–14]. Runoff of rain water can be the cause of the external erosion. The settlements on the crest generate cracks that promote water infiltration into the dam and this could cause internal erosion or slippage in an area

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Fig. 1. Illustration of tailings embankment failure-case of the Mount Polley Mine (Cariboo Regional District, Canada, 2014) [1].

of weakness. It seems relevant to the dam in this study since some settlements on the ridge have already been observed in the past (see Fig. 2).

As noted in Fig. 2, a and b are studied from Google Earth; Fig. 2c is studied by Golder Associates [18].

The Westwood Mine (owned by IAMGOLD Corp.) plans to reuse the TSF #1 for solid waste storage, but on the other side of the Northwest embankment, there is a small water polishing pond (Fig. 2). It was reported that some sporadic and localized slumps and slippage occurred on the embankment. The slippage occurs on the downstream side slope (external instability) and the upstream slope side for some reason (e.g. liquefaction of the tailings or foundation soil as a result of a probable low magnitude seismic event).

The numerical analysis has been widely used to solve complex problems of slope stability, which otherwise would not have been possible using conventional techniques [15–17]. Among other things, geophysical monitoring (electrical methods) can detect the internal cracks in the embankment. Electric resistivity of water is lower than that of rock; variations in the apparent resistivity measured by the electrical method are often correlated with the change in lithology also with the degree of water saturation in rocks (e.g. porous or fractured zones).

2. Methods and materials used

2.1. General methodologies

The aim of this study is to assess the embankment stability by the means of numerical analysis using SLOPE/W and SEEP/W codes and of geophysical methods that use Electrical resistivity [17]. The SLOPE/W code based on limit-equilibrium analysis was used to assess the embankment slope stability analysis through the calculation of the factor of safety (FS) based on the strength reduction factor (SRF) method. Before the simulation with SLOPE/W, the groundwater level (water table) that plays an important role in the stability analysis should be determined. The numerical code SEEP/W has been used repeatedly to find the water table as a function of the variation of the water height in the upstream lake. Electrical method is widely used to detect voids, underground water, fractural zone recognition, and mineral exploration [19–43]. The distribution of water in the different layers corresponding to low resistivity values is in accordance with the high values of water content measured [44]. The difference in resistivity between the target and its surrounding materials is a key factor to ensure that this technique is viable.

2.2. FS (SLOPE/W)

In conventional methods of limit equilibrium analysis, the factor of safety (FS) is defined as the ratio between the resisting forces and the forces leading to movements [17].

$$FS = \frac{\sum S_r}{\sum S_m} \tag{1}$$

where S_r = resisting force due to friction and cohesion; and S_m = driving force tending to drag the block.

Alternatively, the FS can also be expressed as follows:

$$FS = \frac{Moments \text{ resisting sliding}}{Moments \text{ causing sliding}} \tag{2}$$

Amongst the most popular analytical methods of limit equilibrium analysis (see Fig. 3), is the Morgenstern-Price method, which was chosen as the analysis method (which is close to the Spencer's method), because it expresses two basic concepts for determining the FS. The FS versus lambda (Lamé coefficient) indicates the minimum FS at the point of intersection of equilibrium moment and equilibrium force. From Fig. 3, the point of intersection of the moment and the force corresponds to a FS of 2.15 per Morgenstern-Price or Spencer methods. In practice, the use of FS greater than 1.5 for static analysis of embankment stability and steady flow conditions is recommended [15,16,45].

The embankment slope stability is assessed by the effective stress analysis and the Mohr–Coulomb failure criterion was chosen:

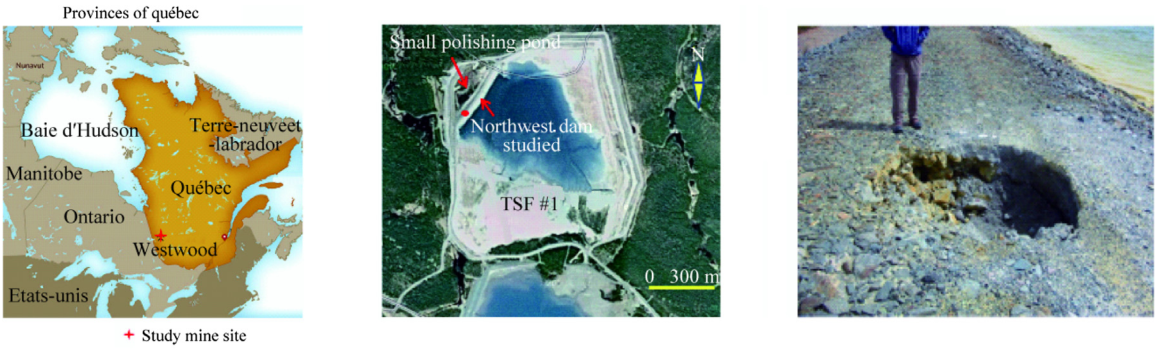
$$\tau = c' + \sigma' \tan \phi' \tag{3}$$

where τ is the shear strength, kPa; c' the effective cohesion, kPa; ϕ' the effective internal friction angle, °; and σ' the effective normal stress, kPa, which is given as follows:

$$\sigma' = \sigma - u \tag{4}$$

where u is the pore water pressure, kPa; and σ the normal or vertical total stress, kPa.

The reduction of the effective stress σ' will reduce the shear resistance and this could promote some instabilities. For each



(a) Its location in Quebec province (b) Tailings area studied (c) Subsidence observed on the Northwest dam

Fig. 2. Location of the Northwest dam.