MANAGEMENT OF SLOPE STABILITY FOR POTASH TAILINGS PILES IN SASKATCHEWAN.

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ABSTRACT

A Tailings Management Area (TMA) slope stability management system has been developed for the Saskatchewan Potash industry that mainly consists of a combination of slope stability analysis, slope stability monitoring (utilizing survey and instrumentation), laboratory testing, and risk review. Appropriate slope stability analysis methods have been formed and continue to be developed. Methods for the successful installation of instrumentation, and recommendations regarding instrumentation requirements have also been developed. The analyses have not been limited to the current configuration of the tailings piles. Recommendations have also been made to the mines regarding the future configurations, such that they may continue to place waste securely. Estimates of tailings pile volumes and storage life have also been provided, so that the mine can develop long-term waste storage and decommissioning strategies.

RÉSUMÉ

Un système de gestion de stabilité de pente de la région de gestion de produits de queue (TMA) a été développé pour l’industrie de potasse de Saskatchewan qui se compose principalement d’une combinaison d’analyse de stabilité de pente, surveillance de stabilité de pente (utilisant l’aperçu et l’instrumentation), l’essai en laboratoire, et la revue de risque. Des méthodes appropriées d’analyse de stabilité de pente ont été formées et continuent à se développer. Des méthodes pour l’installation réussie de l’instrumentation, et des recommandations concernant des conditions d’instrumentation ont été également développées. Le démuni d’analyses limité à la configuration courante des piles de produits de queue. Des recommandations ont été également faites aux mines concernant les futures configurations, telles qu’elles peuvent continuer à placer la perte solidement. Les évaluations des produits de queue empilent des volumes et la durée de stockage ont été également fournies, de sorte que la mine puisse développer le stockage de rebut de long terme et des stratégies de désarmement.

1. INTRODUCTION

Potash mining is conducted at ten mines located in the province of Saskatchewan (Figure 1). Eight of the ten mines in the province use conventional underground mining techniques to recover ore, and the remaining two use solution mining processes. The ore consists mainly of KCl (potash), NaCl (salt), and a small percentage of insolubles (clay, silt, etc). The KCl is separated from the ore in the refinery/mill above ground and the waste product is stored in the Tailings Management Areas (TMAs). Several deposition techniques have been tried for the waste product (mainly salt), but the current method used is to allow a delta to form at the end of tailings slurry lines (spigots) as presented in Figure 2. The spigots are moved around periodically, and heavy construction equipment is used to help control the pile geometry. The maximum height of the potash tailings (salt) piles currently varies from mine to mine from approximately 30 m to heights of 80 m, with slopes of approximately 35°.

There have recently been major slope failures of potash tailings piles in Saskatchewan. Fortunately, the failures have not yet resulted in a loss of life or an environmental release. However, a significant area of the TMA is lost for future development when a failure occurs. There is also a significant risk to ancillary structures, such as dykes and buildings when a slope failure occurs. The approved areas of the current TMA’s are fixed, and therefore, the height of the tailings piles must increase if mining continues. In order for the mines to acquire additional land for waste storage, they must demonstrate that the current TMA has been utilized to full potential. The objectives of this study have been to develop methods for the potash industry in Saskatchewan to manage growth of the tailings piles.

Figure 1 – Location Map
2. SLOPE STABILITY MANAGEMENT MODEL

The TMA management and optimization system was developed on behalf of the Saskatchewan potash industry following the recent slope failures. A schematic representation of the management model is presented in Figure 3. The investigations began with a review of previous investigations relating to the slope stability of the tailings piles. Site investigations were conducted to determine if any instrumentation was available and, if not, recommendations were provided for field investigations. The field investigations typically consisted of the installation and monitoring of piezometers and slope inclinometer casing. Parametric slope stability analysis was performed to evaluate the mechanisms and input parameters that contribute to the slope failures of potash tailings piles. The results of these analyses were used to facilitate planning of instrumentation and monitoring requirements at the sites.

Slope stability monitoring and interpretation of the monitoring commenced at specific sites across the province. In almost all cases, little instrumentation had been previously installed for slope stability monitoring. Additional instrumentation is added each year, with a priority on locations most susceptible to slope failure, or where significant tailings growth is anticipated. Rigorous slope stability modelling was conducted once site specific monitoring data was available to determine current conditions and develop design charts to facilitate future planning of the TMAs.

Pile management decisions are made largely as a result of the stability modelling. Additional investigations to determine the current area, height, and volume of the tailings piles have been conducted to facilitate these investigations. Each year the management system has been improved. The improvements have been related mainly to new instrumentation installations each year as budgets allow. Continuous improvements are also made to reporting methods. These improvements have been made so that the results of monitoring and analyses may be easily communicated to mine personnel who may not have an engineering background.

3. SLOPE STABILITY ANALYSES

Slope stability analysis has been conducted for the majority of the potash mines in Saskatchewan. Limit equilibrium slope stability analyses were used to identify the key parameters controlling the stability of tailings piles. Both deterministic and parametric slope stability modelling was conducted for each of the sites evaluated. The purpose of this work was to determine the current factor of safety, Fs, of the tailings piles, as well as the Fs for various heights and tailings pile configurations (including slope angle and benching of the tailings pile). The sensitivity of the analyses to various input parameters in the slope stability model was also evaluated.

Slope stability that is assessed by a limit equilibrium analysis results in a calculated Fs with respect to slope failure. Using this approach, Fs can generally be expressed according to Equation 1.

\[
Fs = \frac{\text{Resisting Forces}}{\text{Mobilizing Forces}} \quad [1]
\]

Therefore, a factor of safety of unity (Fs = 1) identifies a failure condition according to limit equilibrium theory. The following criteria has been defined for evaluating the results of stability analysis for tailings piles.

- Calculated Fs equal to 1.0 is a condition of almost certain failure;
- Calculated Fs between 1.0 and 1.3 is a high-risk condition; and,
- Calculated Fs greater that 1.3 is a relatively moderate risk condition where the probability of failure is low.

There were four basic elements required for the slope stability analyses:

1. Topography and surface geometry;
2. Stratigraphy or layers of different materials;
3. Engineering properties of materials for each layer; and;
4. Hydraulic conditions in the layers (porewater pressure).

3.1 Topography and surface geometry

The surface geometry of the tailings pile was typically defined using a combination of conventional survey and airborne survey methods. This survey data was used to determine the height and slope angle of the tailings pile at various locations for incorporation into the slope models. Growth of the tailings pile with time is also being continuously evaluated, such that future estimates regarding stability of the tailings piles may also be provided.

3.2 Stratigraphy or layers of different materials

A relatively large amount of information regarding site stratigraphy existed due to previous investigations at the sites. This information was supplemented with the stratigraphy encountered during installation of instrumentation in and around the TMA. Each stratigraphic unit was then represented as a separate layer in the stability model. Additional stability analyses were performed to evaluate the sensitivity of the results to the thickness of the stratigraphic units.

3.3 Engineering properties of materials for each layer

Mohr-Coulomb shear strength parameters (effective angle of internal friction, \( \phi' \), and effective cohesion, \( c' \)) and the unit weight (\( \gamma \)) of each stratigraphic layer (including the tailings), were the properties utilized for the stability analyses. The prevalent foundation soil at many of the sites consists of glacial till. This till represents a relatively competent foundation material, but is often underlain by weaker material such as glacially disturbed shale. Engineering properties for the till units are well documented in Saskatchewan and values adopted for the analyses were based upon previous assessments and/or engineering judgement.

Due to the relatively large natural variation in soil properties, additional stability analyses were performed to evaluate the sensitivity of the results to the properties selected. In situations where little information was available for a particular soil layer, or the analysis results were determined to be particularly sensitive to the values selected, laboratory testing was recommended to define the properties.

The shear strength properties of salt tailings are some of the most difficult parameters to obtain for a limit equilibrium stability analysis. Salt tailings exhibit a dilatant behaviour when being sheared (Fredlund and Mittal, 1989) and are sensitive to the strain rate during testing. Pufahl (1983; Pufahl et al., 1985) completed an extensive research program on the engineering properties of potash tailings. Using direct shear equipment, measured angles of internal friction (\( \phi' \)) of potash tailings ranged from 39° to 45° with essentially zero cohesion. Strength parameters determined using triaxial equipment were shown to have an angle of

internal friction (\( \phi' \)) ranging from 49° to 55° with a cohesion intercept (\( c' \)) ranging from 55 to 270 kPa (Chiu and Fredlund, 1986).

3.4 Hydraulic conditions in the layers (porewater pressure)

Stability analyses completed for the tailings piles in the past often relied upon estimations of porewater pressure, as little actual monitoring was conducted. It was determined from preliminary investigations that stability results were highly sensitive to relatively small changes in porewater pressures in the salt tailings and foundation soils. This was particularly true for the salt tailings, which have a brine mound that develops due to precipitation and the deposition method used (hydraulic discharge of tailings - Figure 2).

Vibrating wire piezometers were installed at select locations in the TMA at several mine sites to evaluate the actual porewater pressures experienced. The height of the brine mound was higher than had been previously estimated at several sites (up to 100% of the pile height during some periods). This had a profound influence on the results of the stability modelling. The height of the brine mound was found to vary significantly from one site to another. It was also found to vary significantly at specific locations based upon past and present mine activities, as well as apparent seasonal effects. Significant excess porewater pressure generation in the foundation soils due to pile loading was also discovered at some sites.

The slope stability models utilized actual porewater pressure data, obtained from monitoring of the vibrating wire piezometers, to determine the current factor of safety. A unique porewater pressure representation was specified for each of the stratigraphic units, based upon the results of monitoring.

3.5 Sensitivity Analysis

Sensitivity analyses were performed following determination of the factor of safety of the tailings piles for the current conditions. The purpose of the sensitivity analysis was to vary selected input parameters, and evaluate the effect on the calculated factor of safety. The input parameters varied consisted mainly of porewater pressures, tailings pile height, thickness of stratigraphic layers (foundation materials), and material properties. Following completion of the sensitivity analysis, design charts were prepared so that the factor of safety of the tailings pile may be estimated for future configurations. An example of the design charts used is presented in Figure 4.
Figure 4 – Design chart showing sensitivity of factor of safety to height of the brine mound for various embankment heights.

4. INSTRUMENTATION

Instrumentation to monitor porewater pressures and slope movement in the TMA have been installed at nearly all of the potash mines in Saskatchewan. Vibrating wire piezometers were selected for monitoring porewater pressure since they may be connected to dataloggers for evaluating trends with time. Several vibrating wire piezometers are often installed in the same borehole using the fully grouted method (Mikkelsen, 2002). Special drilling techniques have been developed for the installation of this instrumentation through the salt tailings (as traditional mud rotary systems cause dissolution of the salt at the borehole). The piezometer locations are most often selected such that a potential failure surface has instrumentation at each side (near the top and toe of the slope). These locations are selected so the porewater pressures may be more accurately estimated for stability analyses in the areas that are important. The piezometers have been installed within, below and around the perimeter of the tailings piles as presented schematically in Figure 5. Real time monitoring of the porewater pressures is also available for areas of significant risk, utilizing dataloggers connected to digital cellular modems and monitoring software.

Slope inclinometers are used for the monitoring of actual slope movements. The slope inclinometers are installed near the toe of the tailings pile, often in conjunction with one or more vibrating wire piezometers (depending upon stratigraphy). The monitoring frequency for the slope inclinometers depends upon the amount of risk associated with the particular piles. Monitoring typically occurs in the spring and fall each year. In situations where active slope movements have been identified, monitoring frequency has increased. In place inclinometers (IPI's) have also been used at locations were an active slope movement is present, and/or there is a significant consequence of failure (risk to mine personnel and/or ancillary structures). The IPI's may be connected to a datalogger so that determinations regarding rate of movement may be made. The dataloggers may also be attached to digital modems, so that remote retrieval of data is possible. This option reduces the cost of monitoring for the mine sites, since it is not necessary to mobilize personnel to the site for each monitoring event.

Figure 5 – Schematic Representation of Vibrating Wire Piezometer Installation Configuration

5. RISK MANAGEMENT SYSTEM

A preliminary risk management model is currently being developed to assist in the management and planning for the tailings piles. The preliminary version of this model is applied by dividing a tailings pile into several representative segments, depending mainly upon slope angle, embankment height, and proximity to ancillary structures. The risk management model was loosely based upon the model developed by Alberta Highways for evaluating landslide risk. Each location and/or segment is then evaluated for two criteria, slope stability, \( F_s \), and consequence of failure, \( C_f \). Risk, \( R \), may then be evaluated according to Equation 2.

\[
R = F_s C_f
\]  

This model presents a way to determine the locations of the tailings pile with the highest priority for monitoring. \( C_f \) may be determined in consultation with mine personnel for each site so that important infrastructure considerations are not missed. The final risk score may be associated with recommended guidelines for action, although these guidelines have not yet been developed. The model may also be used in a predictive manner to determine conditions before the next action is required. This provides mine personnel with guidance relating to areas of the tailings pile that may safely be developed.

6. FUTURE PLANNING

As part of the TMA management and optimization process, future planning for the tailings piles has been incorporated into the investigations. This process is iterative and improving with time, as new data is acquired and additional needs from the minesite are identified. This process has included detailed topographic surveys.
of the tailings piles to determine the current area, height, and volume of the tailings present. Projected waste production volumes from the mines are used to determine the available tailings pile life, considering the results of slope stability analysis and instrumentation monitoring. These studies have been incorporated into future management and decommissioning plans for the mine sites.

7. SUMMARY

The TMA slope stability management system has been adopted by nearly all of the potash mines in Saskatchewan. The investigations conducted provide information that helps the mine sites place the waste securely, and make decisions regarding future planning for the TMA. Additional components are added each year to improve the management system. These improvements consist mainly of additional instrumentation installations, laboratory testing, monitoring and reporting methods. The results of these investigations have been used to manage tailings placement, both in the short and long term.

References