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Geotechnical characterization of the site and stability of a tailings dam in Ecuador

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ABSTRACT: In this paper we present the design and stability analysis of a tailings dam developed in order to stock up tailings from mineral processing plants located in the left bank of Calera river in the Zaruma-Portovelo Mining District, in Ecuador; including a geotechnical study of materials involved. This study first reviews some instability problems that took place in tailings dam in other parts of the world. Then, the geographical and geotechnical characterization of various geological materials (soil, rocks and aggregates) that will serve as a foundation or that will be utilized in the dam construction site is presented. Since some of these materials are ripped and then used to build the dam, they are also characterized according to their granular behavior after set up in the dam construction. Finally, a design fulfilling operational needs is proposed and its stability analyzed in terms of the most probable instability mechanisms (circular failure), and accounting for standard and worst possible hydrogeological and seismic conditions expectable in the area.

1 INTRODUCTION
1.1 Motivation

Tailings, waste products of the ore-dressing processes, are usually stored in a slurry form and pumped to a sedimentation pond which is closed by means of an artificial dam (Ozcan et al., 2013). The database of International Commission of Large Dams (ICOLD) showed that several hundreds of tailings dams have failed since 1910. One of the reasons of these failures is slope instability. Certainly, a number of different accidents associated to tailings dams have been reported in Europe (Rico et al., 2008) and all over the world in the last years in different mining deposits. It is worthy to mention some of the most relevant accidents in Europe: Stava (Italy) in 1985, Aznalcóllar (Spain) in 1998, or Baia Mare (Romania) in 2010 (Figure 1).

Accordingly, the construction and control of tailings dams is presently a matter of safety and environmental concern among mining companies and governmental bodies all around the world.

From some studies and investigations carried out in the last years (Rico et., 2008, USEPA, 1994) including the most relevant tailings dam failures that took place in the last decades, the most common accident reasons were: 1) slope stability, typically sliding of the dam, 2) earthquake, 3) overweight, 4) cementation problems, 5) tubing 6) problems in auxiliary structures, 7) dam erosion, 8) subsidence or field collapse (Rodriguez et al. 2009).

Waste from mining extraction and mineral processing operations are one of the largest waste material flows in the European Union (Quintanilla 2010), and probably in the world. For example, just in Chile, the mining waste volume is estimated to represent more than 500,000 tons per day.

In the Zaruma-Portovelo Mining District, in the province of El Oro in Ecuador, poly-metallic ores are mined in small exploitations. During the last 10 years, the processed volume in the hydrometallurgical plants has grew up in a constant way (in 2010, 2500 t/day were processed). Consequently, there has been a significant increment of liquid and solid waste that should be properly managed, to avoid polluting sulphides and other substances to be released to the local ecosystems.

Figure 1. Some views of the most relevant tailings dam failures occurred in Europe in the past 30 years, including Aznalcóllar dam in Spain, Baia Mare in Romania and Stava in Italy.
The ultimate aim of a tailings impoundment is to contain fine-grained tailings. This has to be carried out in a cost-effective manner that provides for long-term stability of the embankment structure and the impounded tailings and the long-term protection of the environment (USEPA, 1994). Failure of tailings dams may result in disastrous damages to lives, properties and the surrounding environment. In this way, design, construction and operation of the tailings dams require a high level of care in engineering practice (Ozcan et al., 2013).

This article focuses on presenting the background of geotechnical characterization of soils, aggregates and rocks affecting a tailing dams, showing the most relevant variables controlling their stability and presenting an example of a safe particular design in the above named mining zone of Ecuador.

1.2 Problem statement

Portovelo is the principal mining region in the south of Ecuador, where, for decades, mining waste management has been a concern. This waste has so far moderately polluted the Puyango river basin. This river flows into Peruvian national territory and finally into the Pacific Ocean, where it flows out in the town of Tumbes. So to mitigate this problem, it was agreed to build a tailings dam, which could help to avoid further polluting and to clean the river basin.

Several recent researches provided representative examples to improve material characterization facing toward generate reliable studies of tailing dams design. For example, a study published by Ozcan et al. (2013) analyzes the characterization and stability in a structure like this. It is noted the necessity of performing a complete geotechnical study of the affected materials, the determination of the geotechnical characteristics of the aggregate materials and the assessment of the slope stability.

The static and pseudo-dynamic analysis results, based on limit equilibrium methods and numerical approaches, showed that circular failures are the most common critical failure mechanism associated to dam behavior. In this way, the factors of safety tend to diminish as far as the dam is growing in height (Fig. 2). Nevertheless, safety ranges derived by both methods are similar and suitable for dam growing in safety conditions, provided input data are computed in a reasonably accurate way.

2 METHODOLOGY

A number of in-situ and laboratory tests have been carried out in order to characterize dam, tailings and foundation materials. Parameter estimates are based on soil classification systems and direct shear tests, together with and indirect technique to estimate residual granite soil properties (Alejano & Carranza-Torres 2011) and traditional rock mass characterization approaches (Hoek et al., 2002).

The investigation area, called Hacienda ‘El Tablón’, is located 2.5 km south form Portovelo city, in El Oro province, Ecuador (Fig.3). This classification together with simple testing allows a reasonable estimate of strength parameters.

2.1 Determination of geomechanic properties

Six sites were selected to take soil samples and perform geotechnical characterization, in the area that was started to be prepared to build the dam (Fig. 4). The soil amount collected in each site was 2 kg/sample, for the purpose of classifying the soil.
The methodology in this case consists in the utilization of simple equipment, formed by an in-situ pocket penetrometer, that can measure penetration pressure from up to 1 MPa (Figure 5) and the so-called vane-test, which allows an estimate of the shear strength soils and can measure compressive strengths up to 240 kPa. Tests are simple and fast so multiple measurements can be made. The obtained values can be used, in combination with soil classification, to estimate the strength parameters (cohesion and friction) of the residual soil following the approach developed by Alejano & Carranza-Torres (2011). The density was also determined by means of standard techniques.

Additionally, rock mass GSI was obtained at various rock outcrops according to Marinos & Hoek (2000).

All this in-situ information together with some laboratory test permitted to obtain density and strength parameters of all the materials involved in order to estimate the stability of the dam.

2.2 Stability analysis

Considering that the materials which are used in the dam structure are granular materials formed by soils and waste rocks, the most likely and only possible failure mechanism is circular sliding (Ramírez-Oyanguren & Alejano 2008), so this study will be focused on this type failure.

In order to analyze the stability of dams against this type of failures we need to know the geometry of the dam, the strength of the forming materials, the hydrogeological regime and the seismic events to which the dam will be submitted. The worst possible stability conditions are defined in terms of the hydrogeological regime and the highest expected earthquake in the area.

In what concerns the water regime and even if the average annual rainfall is not very high (1200 mm), full saturated conditions for the tailings pond are considered as the worst possible situation. Such conditions could be seldom expected, however a certain degree of conservativeness was thought to be appropriate.

Another relevant factor is the dynamic response of the dam. So the maximum horizontal acceleration derived from recently updated regulations will be contemplated in order to account for worst possible expected seismic situations for a long return period in the construction area.

Once the geotechnical parameters and operative conditions are characterized, a basic design will be proposed and a detailed stability analysis will be carried out in order to check the stability of this design. If this analysis provides unsafe values, convenient design modifications will be provided in order to achieve a safety level in accordance with the international standards and scientific bibliography used.

To analyze stability against circular failure the most suitable methods are those based on classic slices method (derived from limit equilibrium approaches). The program used is SLIDE software from Rocscience (2010). This program implements different slice methods (Bishop, Janbu, GLE, etc...), with the objective to obtain the Factor of Safety (FoS) of slopes. In general, these three methods are considered reliable enough, but the so called General Limit Equilibrium Method (GLE) is meant to provide the most accurate approach.

Additionally numerical methods, as for instance the code Phase2 (Rocscience, 2012), can be used in combination with the shear strength reduction technique (already implemented in this code) to obtain the factor of safety against slope failure. One of the main advantages of this approach is that the code find by itself and based on equilibrium equations the sliding surface. This approach is also followed in this study to check the results obtained by means of limit equilibrium approaches.

3 FIELD CHARACTERIZATION

The field site is located in a mountain valley (Figs. 3 and 4). In this area the outcropping rock is gneiss with a number of pegmatite dykes following the main valley direction. This gneissic rock is often weathered and in large parts of the valley gneiss residual soils are found (INIGEMM, 2013).

3.1 Soils and dam material

6 soils samples were taken in the premises were the dam is to be constructed. 3 Samples were classified as GW-SW and another 3 as ML according to USCS. Additionally vane tests and pocket penetrometer rests were performed in the recovery spots. Following the Alejano and Carranza-Torres (2011) approach, it was possible to estimate the shear strength of this type of materials in terms of Mohr–Coulomb cohesion and internal friction angle values.
Average values of $c = 32.36$ kPa and $\phi = 34.88^\circ$ were obtained. So residual soils were conservatively characterized by $c = 29$ kPa and $\phi = 34^\circ$, representing values of the average minus the standard deviation of results. The natural in-situ specific weight was measured in 17 kN/m$^3$. Based on average results of grain size distribution curves, the permeability was estimated in $5e^{-4}$ m/s.

To characterize the dam material, this soil was extracted, heaped and submitted to a roll flat process in a 0.5 m bed. Results obtained were similar to those of natural soil. Finally selected were reasonably conservative values of $c = 30$ kPa and $\phi = 30^\circ$. The in-situ specific weight was measured in 15 kN/m$^3$ and the coefficient of permeability estimated in $1e^{-3}$ m/s.

3.2 Tailings

A random sampling in 24 accumulation places and treatment plants were made by INIGEMM (2012) in Portovelo region. This sampling allows determining physics properties of wastes, which are going to be stocked up in the tailings impoundment.

Grain size cumulative curves showed that most often mud grain size (0.06 to 0.2 mm) are more common that fine sands (>0.2 mm). Cohesion and friction angle were estimated according to this grain sizes and tests in similar tailing materials performed at INIGEMM (2012). Reasonably conservative values were selected of 5 kPa cohesion and 35$^\circ$ friction. Average specific weight is calculated to be 14.34 kN/m$^3$. Among these parameters, the most influential is the specific weight due to the pressure these fine materials produce on the dike.

3.3 Rock

The rock found in the area is gneiss submitted to different degrees of weathering. For design purposes the rock mass was characterize in its averagely weathered form; since for the purpose of building the dam all the rock material able to be ripped has been removed. In this way the material where the dam is to be founded is weathered gneiss (Fig. 6) not able to be ripped.

This rock mass has been characterize following the approach by Sönmez & Ulusay (2002) to find out an average GSI of 45. For the worst possible conditions encountered where UCS is estimated in 20 MPa (unable to be ripped) and conservative values of $m = 20$ and $D = 1$ are taken, the strength parameter estimate (Hoek et al., 2002) for this weathered gneiss where the dam is to be founded is $c = 120$ kPa and $\phi = 35^\circ$.

At a depth of 3 m the gneiss is considered not to be weathered so their strength parameters have been recalculated to be $c = 1$ MPa and $\phi = 45^\circ$.

3.4 Water regime

Even if the dam will be usually quite dry and a geotextile will cover the down water slope, this study accounts for saturation of the tailings in the pond to reflect worst possible expected conditions.

3.5 Seismic characteristics

Seismic risk was analyzes based on Ecuadorian standards (CEC, 2002), which present the official Ecuador’s seismic zone map (Fig.7). In this map our project is placed in a type II seismic zone, where the maximum expected horizontal acceleration would be 0.25g.

Martínez et al. (2011), based on actual and numerical studies of the response of large earth dams subjected to high intensity earthquakes in Chile concluded that for the case of tailing dams shorter than 100 m, if the design horizontal acceleration is considered half of the maximum horizontal acceleration actually expected, the results will be conservative. In this way, the maximum effective acceleration considered in our safety factor calculations based on pseudo-static analysis is taken to be 0.125g.
4 DESIGN PROPOSAL AND ANALYSIS

In this section a traditional dam design is proposed and its stability against circular failure through the dam or its base is then checked, based on analytical and numerical methods.

Factor of safety (FoS), based on limit equilibrium and numerical methods are estimated for different hydrogeological and seismic conditions to control dam stability under all possible expected conditions. Shall the design be not stable enough, design modifications will be carried out.

4.1 Geometric and geotechnical characteristics

The geometry of the principal dam section is designed by an 80 m long and 20 m high dam with a 1.75:1 (29.74°) external slope and a 1:1 (45°) internal slope (Fig. 8). This permits a length of the tailings pond of 215 m able to content the waste production of the area for 20 years. In addition, an impermeable geotextile will be placed between the dam and the tailings to minimize the leakage of the tailings to the dam. This circumstance will not be considered on the geotechnical study for the sake of conservativeness, and to consider high rainfall periods where the dam could become saturated.

Figure 8. Basic dam design.

All the materials are considered to obey a Mohr-Coulomb strength criterion, they behave in an elastoplastic manner and they can be represented by the parameters shown in section 3. Four possible scenarios are considered including combination of dry and saturated tailing pond submitted or not to seismic vibration ($\alpha = 0.125 \cdot g$, as explained in section 3.5).

4.2 Factor of Safety analysis results using SLIDE and PHASE2

The stability of the slope against circular failure has been studied by means of limit equilibrium with code SLIDE (Rocscience, 2010) and by means of a numerical approach with code Phase2 (Rocscience. 2012). In code SLIDE the Bishop and GLE methods have been followed. In code Phase2 the shear strength reduction technique (SSRT) is used to compute the factor of safety. Outputs of these codes for the worst possible situation conditions are presented in Figure 9. Results for the different situation studied are presented in Table 1.

Table 1. Factors of safety of the tailings dam under different conditions for different analysis techniques.

<table>
<thead>
<tr>
<th>FoS Program</th>
<th>SLIDE</th>
<th>PHASE2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>Bishop</td>
<td>GLE</td>
</tr>
<tr>
<td>Dam conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry, no quake</td>
<td>2.18</td>
<td>2.18</td>
</tr>
<tr>
<td>Dry and $\alpha = 0.125 \cdot g$</td>
<td>1.69</td>
<td>1.67</td>
</tr>
<tr>
<td>Saturated and no quake</td>
<td>1.68</td>
<td>1.68</td>
</tr>
<tr>
<td>Saturated and $\alpha = 0.125 \cdot g$</td>
<td>1.30</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Table 1 indicates that the dam will be stable in all possible situations including dry and saturated conditions under the effects of an earthquake or not. Additionally, in the worst possible situation with the saturated dam submitted to large quake, a FoS around 1.3 is kept. Such situation can be expected only once every 10 years.

Since the main aim of this study was to guarantee the dam stability analyzing the FoS of the most critical failure, these results based in reasonably accurate but moderately conservative parameters can ensure the stability of the dam.

In all cases, the factor of safety obtained (FoS > 1.25) is suitable according to technical literature and safety standards related to this kind of structures (ITC, 2000), even in the worst possible case.

4.3 Sensibility analysis from extreme case

In order to determine the robustness of the approach and also to put forward which parameters are more relevant to stability, a sensitivity analysis is carried out for the GLE approach in the worst possible scenario (saturated pond with earthquake). This analysis consists in recalculating the FoS based on the systematic change of every relevant parameter –
cohesion, friction angle, seismic acceleration and apparent specific weight. In this analysis, each parameter is changed ±50%, ±25% and ±10%, and factors of safety were computed in each case. Results are presented in the shape of a spider diagram as Figure 10 illustrates.

![Sensitivity chart for the stability of the dam analysed by means of GLE (SLIDE)](image)

Figure 10. Spider diagram or sensitivity chart of the stability analysis of the dam for worst possible conditions and by means of code SLIDE, with the GLE approach.

From the results obtained, the most relevant control parameter on stability is the friction angle; however variations over 30%, which would take the FoS near 1, are not expected, so stability is guaranteed. Cohesion affects less significantly, so a decrease of up to 50 % will keep the dam stable. This approach contributes to a better reliability of the design approach carried out.

5 CONCLUSIONS

In this study, a series of geotechnical experiments were conducted on the construction material and tailings of a tailings dam at a mining area in Ecuador. A dam design was proposed and its stability was investigated under static and dynamic conditions. The results, which were obtained both from limit equilibrium methods of analysis and numerical modelling, were evaluated to provide a safe design for the dam.

Additionally, based on the obtained results, the following conclusions can be drawn. The analysis results obtained from the limit equilibrium methods and numerical modelling showed a good agreement and indicated that the most critical failure modes are basically circular failures passing near the external toe of the dam.

According to the results obtained from method of analysis, the minimum safety factors calculated for the current dam under dynamic conditions are 1.28. This is a sufficiently safe value, and moreover the sensitivity analysis has further demonstrated that the most sensitive parameters in dam stability are friction and cohesion, and since they have been conservatively estimated, the stability of the dam is ensured. The proposed methodologies have revealed to be adequate for geotechnical characterization and factor of safety estimation.

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