# Determination of a tailings storage facility capacity via finite-element and finite-strain methods

**Waldo Huallanca[1], Andrés Reyes[1], Denys Parra[1] and Dirk van Zyl[2]**

1. *Anddes Asociados, Peru*
2. *The University of British Columbia, Canada*

## ABSTRACT

Mine operators often encounter the problem of predicting the storage capacity of tailings storage facilities (TSF) for different productions schedules and stages of mine development. The consolidation phenomenon in tailings is crucial for the long-term behaviour of TSF in order to avoid the over or underestimation of its final storage capacity and filling time. Over the last years, techniques such as the finite-element and finite-strain methods have been extensively used to determine the settlement of tailings due to the consolidation. The two-dimensional (2D) finite-element approach is usually implemented using software such as PLAXIS, while the finite-strain method is based upon the model developed by Gibson et al. (1964) and later expanded by other researchers.

This paper presents a case study consisting of consolidation analysis and determination of the storage capacity and filling time of one of the deepest TSF projects in an open pit in Peru, with 350 m of maximum depth. The analysis took into consideration the concept of tailings mass conservation and used an iterative production schedule in a PLAXIS finite-element model. In addition, the finite-strain three-dimensional upper and lower bound solutions for the method based on Gibson's theory were used for comparison purposes.

The mass-conservatiion and iterative analysis based on the finite-element approach proved to be useful for the optimization of the storage capacity and filling time, design and production schedule for the TSF. Furthermore, the results of the finite-strain method allowed a detailed comparison of the two techniques to determine the actual storage capacity and filling time of TSF based upon tailings consolidation. Finally, the magnitude of the consolidation results highlighted the importance of these analyses for a deep TSF during design and operation, even during feasibility stages.

**Keywords:** tailings, consolidation, storage capacity, filling time

## INTRODUCTION

Mine operators and designers usually deal with the problem of predicting the TSF storage capacity during a determined period of time for different production rates, schedules and stages of mine development. The prediction of TSF storage capacity is relatively difficult to perform only by using an average dry density for the whole facility, which is common in small TSFs with heights up to 30 m. Consequently, in order to avoid the over or underestimation of the final storage capacity and filling time of TSF, the management of the consolidation process in tailings is a key issue for the long-term behaviour of these materials. This is particularly important for a TSF located in open pits due to its large size and depth, where the magnitude of the consolidation phenomenon on tailings significantly impacts the final storage capacity.

This paper presents a case study of one the deepest TSF projects in an open pit in Peru, with 350 m of maximum depth, where a consolidation analysis was carried out in order to properly determine the storage capacity. The analysis was performed using the finite-element method through PLAXIS and the finite-strain method based upon the model developed by Gibson et al. (1967) and improved by other researchers. The objective is to compare these approaches and demonstrate the importance of the careful assessment of the consolidation of tailings and its impact on the maximum storage capacity of TSF.

## METHODOLOGY

This paper approaches the calculation of tailings through two methods: the finite-element and the finite-strain. The following sections describe both methods.

### Finite-element method

The generic finite element modelling program PLAXIS was employed for the first approach. This software uses an arbitrary lagrangian eulerian (ALE) coordinate system (Priestley, 2011). Generally, ALE formulations are preferred for very large deformations, as they allow for very large deformations to be modelled without the need for constant re-meshing as the mesh is either allowed to move according to lagrangian principles or remain static according to eulerian principles (Donea et al. 2004). The Soft Soil (SS) model (Brinkgreve et al., 2014) was employed on the numerical modelling and was calibrated using simulations of consolidation tests. The SS model is a Cam-Clay type constitutive model implemented in PLAXIS specifically meant for primary compression of near normally consolidated clay-type soil. Some of the features of the SS model include a stress dependent stiffness (based on a logarithmic compression behavior), distinction between primary loading and unloading-reloading, failure behavior according to the Mohr-Coulomb criterion, among others (Brinkgreve et al., 2014).

The procedure to assess consolidation phenomenon during the filling process of the TSF through the finite-element method was as follows:

- An initial filling curve is determined assuming an initial dry density, not taking into account any consequences of consolidation.
- The two-dimensional (2D) PLAXIS cross-section is built. The tailings to be deposited are modeled and horizontally discretized in several clusters.

- An initial consolidation analysis is carried out, considering the time needed to fill each cluster according to the initial filling curve. Resulting void ratios are calculated for each cluster.
- A second filling curve is built taking into account the different void ratios for each cluster (and corresponded tailings height) that resulted from the consolidation process for the initial times. New dry densities are calculated based on the void ratios that resulted from the consolidation analysis. Consequently, this second curve is based in higher dry densities varying in depth and increasing the time needed to fill each cluster.
- The PLAXIS model was run again only modifying the consolidation times for each cluster, based on the new curve. These updated PLAXIS results are subsequently used to built a third filling curve. The procedure is repeated until convergence is reached, meaning that the resulting void ratios from the last model are equal to the previous one.
- The last filling curve takes into account the instantaneous consolidation process and increased the storage capacity of the TSF by increasing consolidation times for each cluster.

**Finite-strain method**

The finite or large-strain consolidation theory proposed by Gibson et al. (1967) allows for the non-linearity of tailings material properties and can be readily applied to estimate void ratio profiles for one-dimensional (1D) tailings deposition scenarios (Gjerapic et al., 2008). The method used for this paper is a mass-conservation scheme presented by Gjerapic and Znidarcic (2007) and detailed by Gjerapic et al. (2008). They also present upper and lower bound solutions for a three-dimensional (3D) tailings deposition problem that can be readily applied to determine the required impoundment capacity for various deposition rates and impoundment geometries. Their proposed solutions account for the tailings compression as the height of the TSF increases.

The upper and lower bound solutions utilize a series of 1D tailings columns calculations. The 3D model behaviour is calculated by summing the geometries of 1D side-by-side columns. Consequently, the proposed solutions implicitly assume that the effects of horizontal drainage and lateral displacements are negligible, an assumption that is acceptable for the vast majority of conventional TSF scenarios (Gjerapic et al., 2008). The procedure followed for this paper is detailed by Gjerapic et al. (2008); the spreadsheets employed were presented by Van Zyl et al. (2014).

## CASE STUDY GENERAL BACKGROUND

The case study is for a TSF design project in the feasibility study stage, located in southern Peru, for one of the most important copper mines in the region. Its existing open pit, which is shown in Figure 1 and has a maximum depth of 350 m, will be used to store the future slurry tailings production with a deposited solids content of 58%. Mine operators required an accurate estimation of its storage capacity to properly define a production schedule and plan its operation. Given its large size, it was clear that the consolidation of tailings would significantly impact its final storage capacity. Figure 1 shows a satellite view of the open pit by the year 2014 and Figure 2 presents its geometric characteristics.

**Figure 1** Panoramic and satellite plan view of the open pit by the year 2014

## CONSOLIDATION ANALYSIS

Several standard 1D and seepage induced consolidation tests were carried out, along with standard geotechnical tests, to properly characterize the tailings deformational behaviour. These tests allowed for defining the parameters used in the finite-element and finite-strain analyses. Table 1 and Table 2 present the parameters for the SS model and finite-strain model, respectively. A, B, C, D and Z are material parameters determined from laboratory tests and are based on the constitutive relationships presented by Abul-Hejleh and Znidarcic (1994, 1996). Figure 3 shows the compressibility and hydraulic conductivity curves. It was acknowledged, however, that the SS model only adequately model the small strain aspects of consolidation. In contrast, the parameters employed for the finite-strain model were more suitable for large strain consolidation. For both methods, impervious boundary conditions were considered for a conservative approach.

**Table 1** Geotechnical parameters of the soft soil model

| Total unit weight (kN/m$^3$) | Saturated unit weight (kN/m$^3$) | $C_c$ | $C_s$ | Initial void ratio | Friction angle (°) | Cohesion (kPa) | Hydraulic conductivity (m/day) |
|---|---|---|---|---|---|---|---|
| 11,8 | 17,4 | 0.17 | 0.017 | 1.3 | 5 | 10 | 8.7 E-3 |

**Table 2** Geotechnical parameters for the finite strain analyses

| Gs | A (kPa$^{1/B}$) | B | Z (kPa) | C (cm/seg) | D |
|---|---|---|---|---|---|
| 2.7 | 1.55 | -0.0909 | 6 | 4E-5 | 4.4936 |

The finite-element model in PLAXIS followed the procedure described previously. The initial filling curve was built using and initial average dry density of 12.0 kN/m$^3$. Ten horizontal clusters with different heights, varying from 14 to 50 m, were used to discretize the 2D model. It is important to mention that the PLAXIS approach considered the real production curve until the 18$^{th}$ year of operation, which is shown in Figure 4. After 4 iterations, convergence was reached. Figure 5 shows the final void ratios for the last iteration and the influence of the geometry on these values. As can be seen in Figure 5, the larger values were obtained on the top and the sides of the open pit, showing the influence of the fixed boundary conditions. Some corners experienced numerical instabilities for the void ratio values that were eventually overcome for longer consolidation times. The last layers also exhibited slightly larger values of void ratio due to immediate settlements and were not shaded; these layers stabilized also for longer consolidation times. The final iteration provided the actual storage capacity and corresponded filling time.

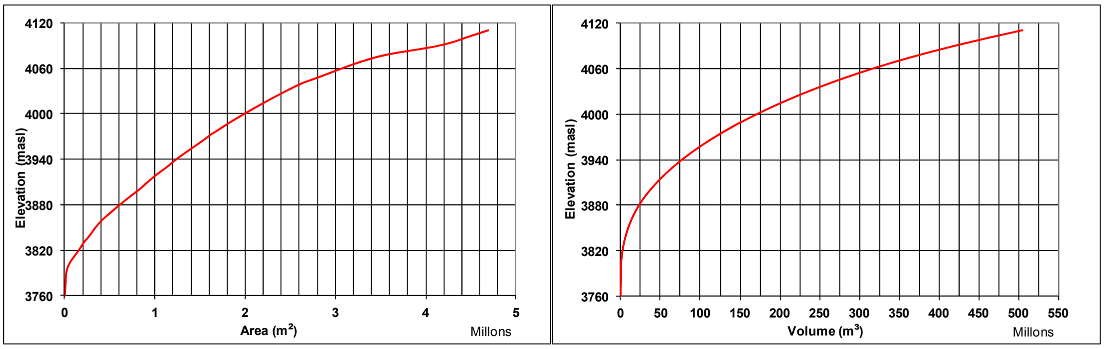


**Figure 2** Geometric characteristics of the open pit

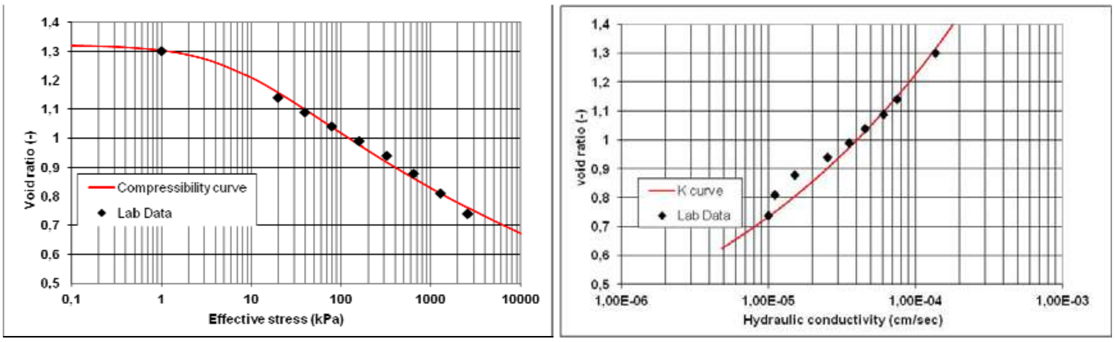


**Figure 3** Compressibility and hydraulic conductivity curves

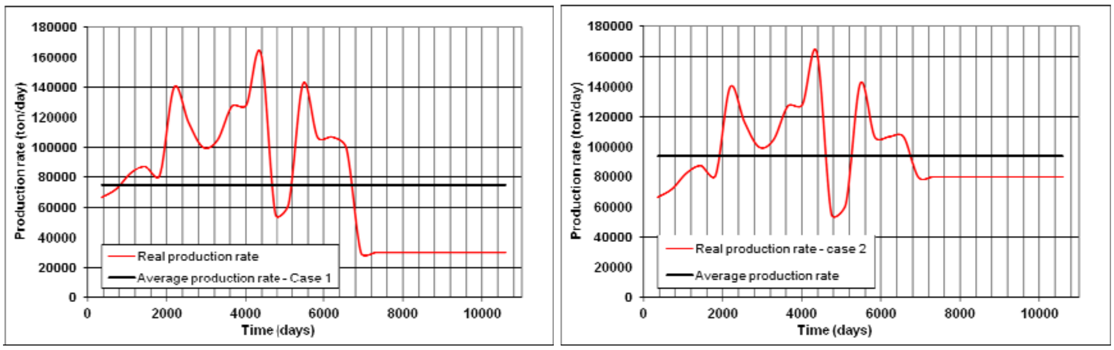


**Figure 4** Daily production rate for case 1 (left) and case 2 (right)

The finite-strain approached followed the procedure described by Van Zyl et al. (2014). In order to simplify the procedure, an average filling ratio was considered for first steps of the analysis. Two cases were considered: the first one considered a decline of production on the 18th year of operation. The second case considered higher production after this year. Both cases are shown in Figure 4. As mentioned before, the PLAXIS approach only took into account production until the year 18 according to its final filling time. Six horizontal clusters with different heights, varying from 50 to 60 m, were used to discretize the 3D open pit problem into 1D columns.

The schematic filling stages of these clusters are shown in Figure 6. The upper and lower bound solution were calculated similarly to the produce described by Gjerapic et al. (2008) and Van Zyl et al. (2014). However, to include the variability of the production rate, only the first iteration of the solutions considered the average production rate described before. Subsequent iterations considered specific average production rates for each cluster according to the real production rate curve shown in Figure 4 for both cases. Four iterations were required to reach convergence.

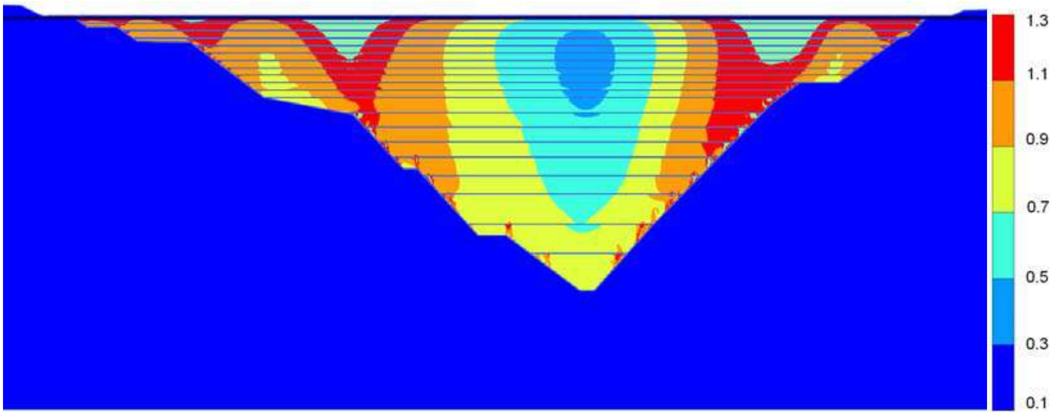


**Figure 5** Void ratios for the final iteration of the finite element approach (at day 6802)

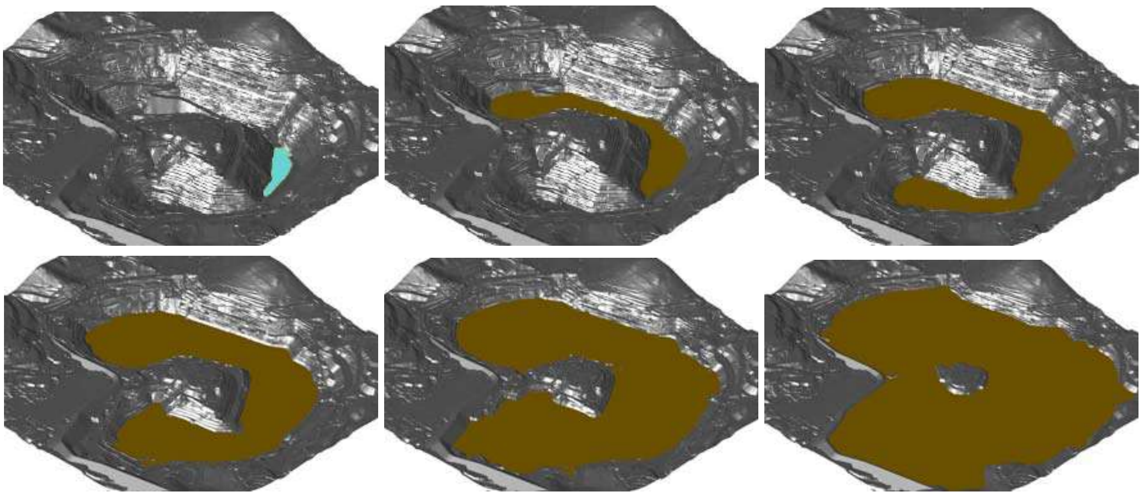

**Figure 6** From top left to bottom right: schematic view of the open pit filling staged corresponding to 3820, 3880, 3940, 4000, 4060 and 4110 masl.

Figure 7 shows the cumulative production resulting from the upper and lower bound solutions for cases 1 and 2, as well as the PLAXIS result. Table 3 shows the filling time and storage capacity for all the cases analysed.

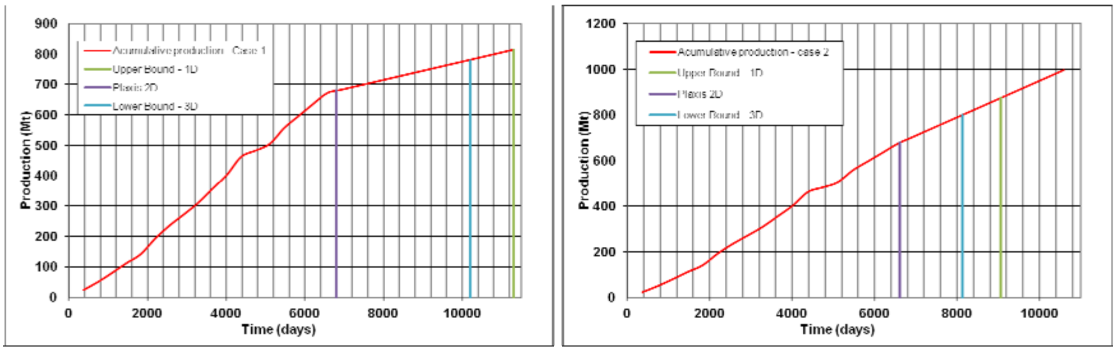


**Figure 7** Cumulative production and results for both approaches for case 1 (left) and case 2 (right)

**Table 3** Results

| Case and approach | Filling time (day) | Filling time (year) | Storage capacity (Mt) | Average total unit weigh (t/m³) |
|---|---|---|---|---|
| **Case 1** | | | | |
| PLAXIS | 6802 | 18.64 | 680 | 1,31 |
| Upper bound | 11 300 | 30.96 | 814 | 1,56 |
| Lower bound | 10 200 | 27.95 | 778 | 1,50 |
| **Case 2** | | | | |
| PLAXIS | 6802 | 18.64 | 680 | 1,31 |
| Upper bound | 9060 | 24.82 | 874 | 1,68 |
| Lower bound | 8132 | 22.30 | 800 | 1,54 |

## CONCLUSIONS

Finite-element and finite-strain approaches to assess the consolidation phenomenon of tailings were explored and applied to evaluate tailings deposition into a 350 m-maximum-depth open pit in southern Peru. The generic finite element modelling program PLAXIS was used to model a 2D cross-section of the open pit. The mass conservation scheme presented by Gjerapic and Znidarcic (2007) was used to develop upper and lower bound solutions using the lagrangian consolidation theory proposed by Gibson et al. (1967).

Several 1D consolidation and seepage induced consolidation tests were performed on tailings to determine its consolidation parameters. The SS model (Brinkgreve et al., 2014) was used in finite-element model and the constitutive relationship presented by Abul-Hejleh and Znidarcic (1994, 1996) was used in the finite-strain model. These two approaches used to model the deformational behaviour of tailings were considered appropriate since the initial void ratio was of 1.3, which is a relatively low value.

The proposed technique for the finite-element approach proved to be conservative, calculating storages capacity 12 to 15% lesser than the lower bound solution of the finite strain method. Through a relatively fast computational time, convergence of the technique was achieved. However, 3D effects are neglected and limitations are encountered when approaching large strains.

The finite-strain method proved to be computational efficient in calculating the storage capacity of the TSF. The upper bound solutions determined a storage capacity 5 to 10% higher than the lower bound solution, the latter one being considered the most accurate when compared to real 3D consolidation analysis (Van Zyl et al., 2014). The comparison made for case 1 and 2 production rates showed that differences between the upper and lower bound solutions are lower for case 1 because the last staged of filling provided a longer consolidation time. Case 2 showed larger differences for these solutions due to higher production rate that does not provide enough time for the consolidation of tailings. The finite-strain approach also proved to be computational efficient and managed to include a pseudo-3D effect.

Initial estimations of the filling time via the finite-strain method proved its sensitivity to the consolidation parameters selected. Similarly, the production rate is one of the most important variables when estimating both the storage capacity and filling time.

Assessment of the consolidation phenomenon of tailings proved to be crucial in optimizing the TSF storage capacity and planning, production schedule and overall development of the mine. Simple calculations such as steady state consolidation analysis may overestimate the storage capacity. Finally, the magnitude of the consolidation results highlighted the importance of these analyses for a deep TSF in their design and operation, even during feasibility stages.

## REFERENCES

Abu-Hejleh, A.N. and Znidarcic, D. (1994) *Estimation of the consolidation constitutive relations,* Computer Methods and Advances in Geomechanics, Siriwardane & Zaman (eds) Balkema, Rotterdam, pp. 499-504.

Abu-Hejleh, A.N. and Znidarcic, D. (1996) *Consolidation characteristics of phosphatic clays,* Journal of Geotechnical Engineering, ASCE, New-York, Vol. 122(4), pp. 295-301.

Brinkgreve, R.B.J., Engin, E. and Swolfs, W.M. (2014) PLAXIS 2014 Material Models Manual. Plaxis bv, Netherlands.

Gibson, R., England, G. and Hussey M. (1967) *The theory of one-dimensional consolidation of saturated clays, I. finite nonlinear consolidation of thin homogeneous layers,* Géotechnique, vol. 17(3), pp. 261–273.

Gjerapic, G., Johnson, J., Coffin, J. and Znidarcic, D. (2008) *Determination of tailings impoundment capacity via finite-strain consolidation models*, in GeoCongress 2008 - conference proceedings, Akram N. Alshawabkeh, Krishna R. Reddy and Milind V. Khire Eds., March 9-12, New Orleans, Louisiana, pp. 798-805.

Gjerapic, G. and Znirdardic, D. (2007) *Mass-conservative numerical solution for finite-strain consolidation during continuous soil deposition*, Geo-Denver 2007: Computer Applications in Geotechnical Engineering - conference proceedings, Siegel, T.C., Luna, R., Hueckel, T. and Laloui. L., Eds., February 18-21 Denver, Colorado.

*Capacity via Finite-Strain Consolidation Models city*, short course presentation, Tailings and Mine Waste ’14 Conference, October 5, 2014, Keystone, Colorado, USA. This is the same as Van Zyl, et al, 2014 below. Remove one of them and make sure that the reference in the text is also corrected.

Donea, J., Huerta, A., Ponthol, J., Rodirguez-Ferrari, A. (2004) *Arbitrary Lagragian-Eulerian methods, In Encyclopedia of Computational Mechanic.*

Priestley D,. (2011) *Modelling multidimensional large strain consolidation of tailings,* MASc Thesis. Vancouver: The Faculty of Graduate Studies of University of British Columbia.

Van Zyl, D., Znidarcic, D. and Gjerapic, G. (2014). *Modeling Aspects of Tailings Disposal Facility Design - Prediction of Storage Capacity*, short course presentation, Tailings and Mine Waste '14 Conference, October 5,, Keystone, Colorado, USA.