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FLAC-based modelling of tailings deposition and consolidation

Alessandro Amodio, Hongjie Zhou & Noel Boylan
Norwegian Geotechnical Institute, Perth, Australia

1 INTRODUCTION

Tailings is often discharged within storage facilities in a slurry state, and it passes through flocculation and sedimentation stages before commencing a consolidation process. The consolidation occurs under tailings self-weight with gradual deposition of the material. Generally, at the end of the discharging, wick drains are installed to speed the consolidation and then backfilled with waste rocks to reclaim the mining site.

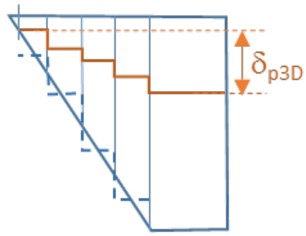
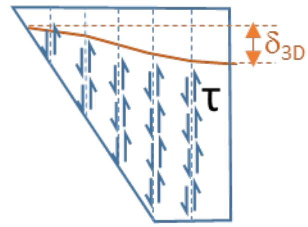
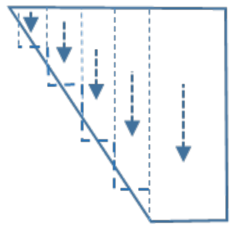
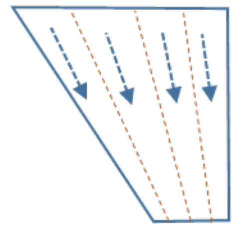
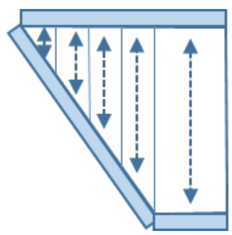
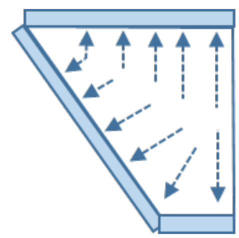
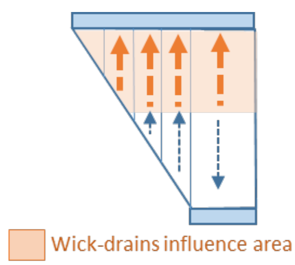
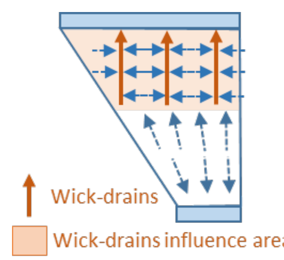
A proper model of the physical process of deposition and consolidation is necessary for a reliable estimate of the capacity of the storage facilities and the management of various production schedules and stages of mine development. Consolidation of tailings presents a challenge at nearly all mines and this does not only affect the estimation of the total impoundment capacity and the post-closure settlements but also the expression of pore water over time. An approach that can simulate gradual tailings deposition and large strain consolidation can be a powerful tool to guide projects through planning and monitoring stages.

This extended abstract presents a multi-dimensional modelling approach developed to overcome the numerical challenges faced in the modelling of tailing deposition and consolidation, after a brief description of the current state of practice. It describes the most significant verification performed and provides description of an example application.

2 STATE OF PRACTICE REVIEW

To date, many 1-D large-strain consolidation computer programs have been developed and are adopted in mining practice for assessing the consolidation settlement of tailing. For complex multi-dimensional problems, several 1-D calculations can be joined together to approximate the multi-dimensional problem, which can be called a "pseudo-3D" approach. This approach is based on the 1-D column consolidation models, where the three-dimensionality of an impoundment is approximated as a number of concentric annuli of varying heights and areas or a series of sequential stacked columns (e.g. Gjerapic et al. 2008). Although most of these programs have been proved to work for 1-D problems, their performance varies when modelling real full-scale problems, with significant limitation for the cases with irregular impoundment geometry, complex (e.g. non-vertical) drainage paths, nonhomogeneous distribution of tailings, etc. Most of these limitations can be overcome by using multidimensional model (as it is summarized in Table 1).

Table 1. Pseudo-3D calculation vs. multi-dimensional modelling.

Comments	**Pseudo-3D Calculation**	**Real multi-dimensional modelling**
Interaction between the columns is ignored in the pseudo-3D analysis, which leads to over-estimation of the differential settlement, i.e. $\delta_{p3D} > \delta_{3D}$		
Only vertical deformation is considered in the pseudo-3D analysis. A multidimensional model can capture the volumetric deformation toward the center of the impoundment, due to the inclination of the side wall of the impoundment.		
Pseudo-3D analysis cannot model non-vertical flow explicitly, while the non-vertical flow may make significant difference, due to higher horizontal k and permeable boundaries.		
Pseudo-3D analysis cannot model wick drains explicitly.		

3 TECHNICAL CHALLENGES

3.1 *General*

The developed modelling approach proposed by NGI is built on *FLAC* (Itasca 2016) but includes various extensions necessarily made using the built-in *FISH* coding language. These extensions can be classified into two categories:

- User define constitutive modelling, which captures the key features of the tailings' behavior during large-strain consolidation.
- Modelling procedure, which can simulate gradual deposition of tailings into the impoundment.

3.2 *User Define Constitutive Model*

The non-linear relationships of e-σ' and k-e has been implemented by modifying the built-in Mohr-Coulomb model in *FLAC* (Itasca 2016). During the analysis, the values of the voids ratio for each element is firstly updated after every step of calculation according to the computed volumetric strain, followed by update on the density, stiffness and permeability.

Since the constitutive models in *FLAC* operate in incremental fashion, the elastic moduli (e.g. bulk and shear modulus) required in *FLAC* input are tangent moduli, and they are used to relate incremental stresses to incremental strains. It is worth noting that the use of incremental algorithm in *FLAC* is an important feature for the present modelling. This enables the implementation of the non-linear e-σ' relationship.

Comparing to the Cap-yield model (Itasca 2016), provided in *FLAC*, the modified Mohr-Coulomb model by NGI provides more flexibility in modelling the void ratio-effective stress relationship. In the Cap-yield model the relationship is controlled by the shape of the cap hardening function with limited flexibility in the variation of the material compressibility with the hardening process.

Because of the feature of this model, which allows for significant hardening during consolidation, one of the key challenges is represented by the large differences of the stiffness properties within the model during the consolidation analyses, e.g. between the elements at the top (subject to negligible effective stress) and those at the bottom (already consolidated to a significant stress). In order to overcome these challenges several sub-routines have been developed within the user define constitutive model to regulate the water bulk modulus according to the calculated stiffness.

3.3 *Deposition modelling*

In order to simulate the gradual deposition of tailings, a staged-filling approach has been developed in combination with the built-in large-strain calculation mode of *FLAC* (Itasca 2016). Each deposition stage (i.e. activation of one new layer above the existing tailings in the impoundment) is performed in undrained manners and it is followed by a period of consolidation.

Typically, the tailings are assumed to be deposited continuously in the impoundment while maintaining a horizontal surface (assuming no shear strength for the slurry). This is simulated exactly by the developed staged filling approach. For each newly activated layer, the top surface is purely horizontal while the bottom is deformed according to the consolidation settlements produced during the previous deposition stages. With this approach, different local deposition rates (i.e. deposition rate per unit area) are considered in the modelling, with more tailings material deposited in area which experience more settlements (often corresponding to the deep part of the impoundment). Note that this calculation approach could not be easily developed with other commercial software but *FLAC* because of the exclusive capability of this software to specify the geometry of newly activated elements just before the activation. In this case the newly activated elements are shaped according to the settlements occurred.

The consolidation time for each consolidation stage is computed according to the assumed deposition rate and the volume of the new layer (calculated with a script at the beginning of the undrained stage).

The main challenge for the deposition modelling is the frequent update of the boundary conditions with the activation of new elements. In order to prevent numerical instability a number of sub-steps have been introduced within the process of the element activation, update of total stress and excess pore pressure.

3.4 *Validation*

Various rigorous verifications and validations have been performed in the course of developing the modelling approach. The constitutive model has been tested with element model in uncoupled and coupled analyses with small and large strain mode; the gradual deposition modelling approach has been validated against the analytical solution developed by (Gibson 1958) and the predictions presented in (Townsend & McVay 1990) have been used to validate the model performance under different scenarios. Note that (Townsend & McVay 1990) summarized results of a prediction competition where nine teams of modelers predicted consolidation behavior of four different waste clay disposal scenarios using 1D models and the results are commonly used as a benchmark for the evaluation of numerical models of large-strain consolidation.

Due to space limitation, only the results of the validation against two scenarios from (Townsend & McVay 1990) are reported on Figure 1. The results of the verification exercise against all the scenarios from (Townsend & McVay 1990) is presented in (Zhou et all. 2019). The two scenarios depicted on

Figure 1 represents the most complex among those presented in (Townsend & McVay 1990); this is also testified by the low number of modelers that managed to provide prediction for these scenarios (e.g. only three prediction out of nine modelers are reported for Scenario D). As shown below, the developed modelling approach achieves excellent results in comparison with predictions made by the participants. This provide great confidence in applying the model to real complex multi-dimensional continuous deposition and large strain consolidation problems.

4 EXAMPLE APPLICATION

A full-scale example has been modeled and presented in this document to demonstrate the capability and performance of the developed modelling technique. An axisymmetric model has been considered and the tailings is assumed to be discharged at a constant rate (of 2 Mt per month). Typical copper mine tailings material has been considered (Tito 2015).

Backfilling of rock at the top of the tailing is considered as a part of mine closure. Wick drains are installed 1 year after the tailings deposition is completed. They extend from the top of the tailings to 30 m below the tailing surface. The wick drains are modelled with zero excess pore water pressure boundary conditions combined with an 'equivalent' permeability (estimated based on our experience and research findings in the public domain e.g. Barron 1948, Hansbo 1981, Nguyen et al. 2018).

Zero excess pore pressures are assumed along the base and walls of the impoundment. A bonded interface is assumed between the tailings and side wall and base of the impoundment, though any intermediate interface conditions (between smooth and rough) can be modelled if necessary.

The development of tailing consolidation settlement with time, the amount of water expressed during consolidation, as well as the capacity of the pit for tailings storage (depending on the quantity of the rock for backfilling) can be estimated from the model.

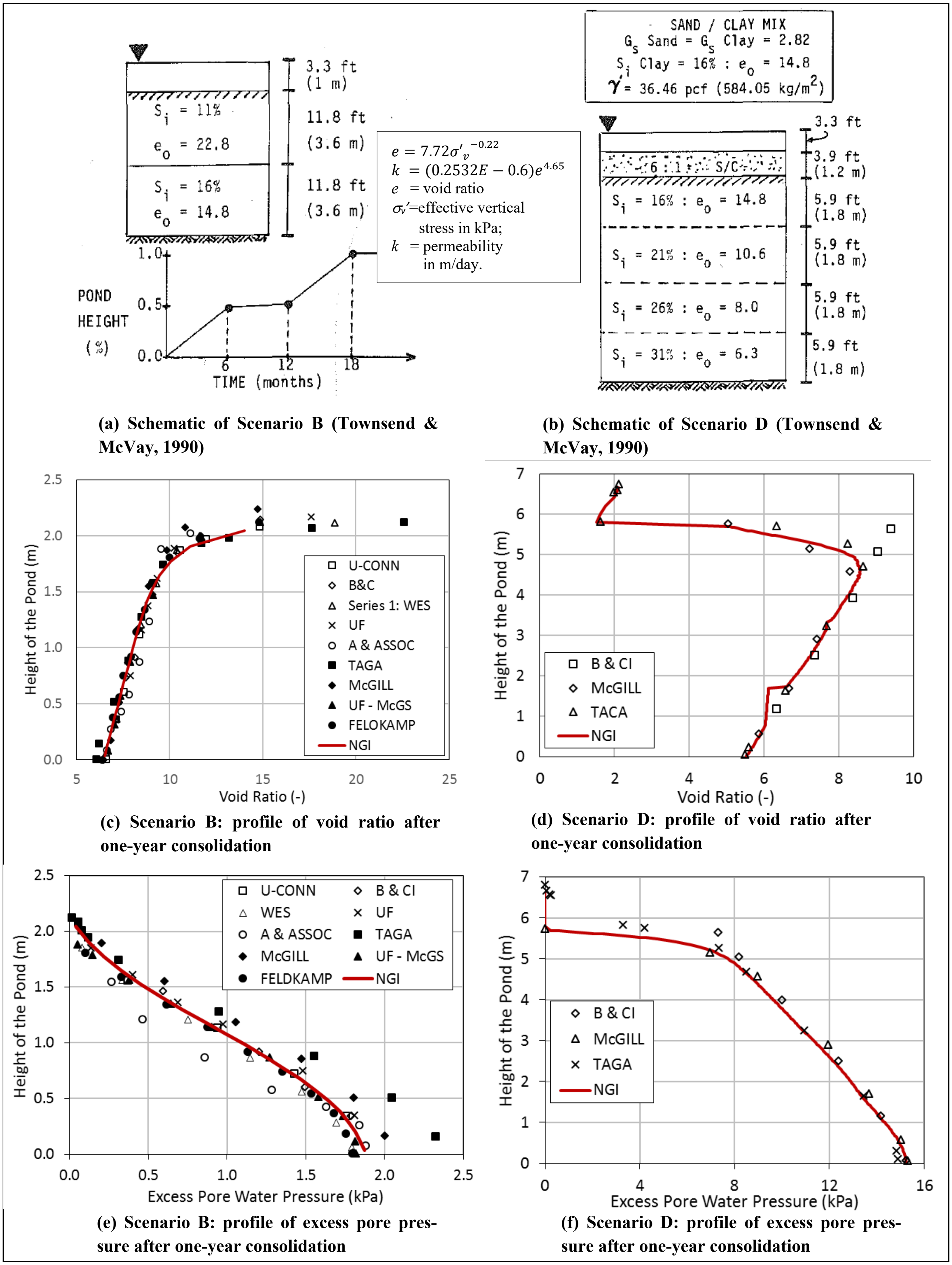
The variation of tailings voids ratio with different deposition and consolidation stages is plotted on Figure 2. In the process, the voids ratio reduces gradually from the bottom of the impoundment. The wavy distribution of the voids ratio is due to the inclusion of wick drains.

5 CONCLUSIONS

Based on foregoing discussion, comparisons, and example modelling, the following conclusions can be reached:

- Modelling of full-scale tailings consolidation is often performed using 1-D models or a variant of these models referred to as 'pseudo-3D' which implies significant approximations.
- There is a need to develop full scale multi-dimensional modelling approaches to improve the prediction of tailings consolidation.
- The developed NGI modelling approach has shown to provide excellent predictions. This approach is believed to perform at a consistently reliable level, regardless of the complexity of the problem.
- Since the approach is built on a commercial software (*FLAC*), it is not only reliable and powerful, but also highly portable.

There is also great potential in further extending the capability of the modelling approach. Further development is ongoing in order to maximize its functionality, such as prediction of the increase in tailings strength with consolidation to improve prediction of tailings dam stability.



(a) Schematic of Scenario B (Townsend & McVay, 1990)

(b) Schematic of Scenario D (Townsend & McVay, 1990)

(c) Scenario B: profile of void ratio after one-year consolidation

(d) Scenario D: profile of void ratio after one-year consolidation

(e) Scenario B: profile of excess pore pressure after one-year consolidation

(f) Scenario D: profile of excess pore pressure after one-year consolidation

Figure 1. Validation against Scenario B and Scenario D from (Townsend & McVay 1990).

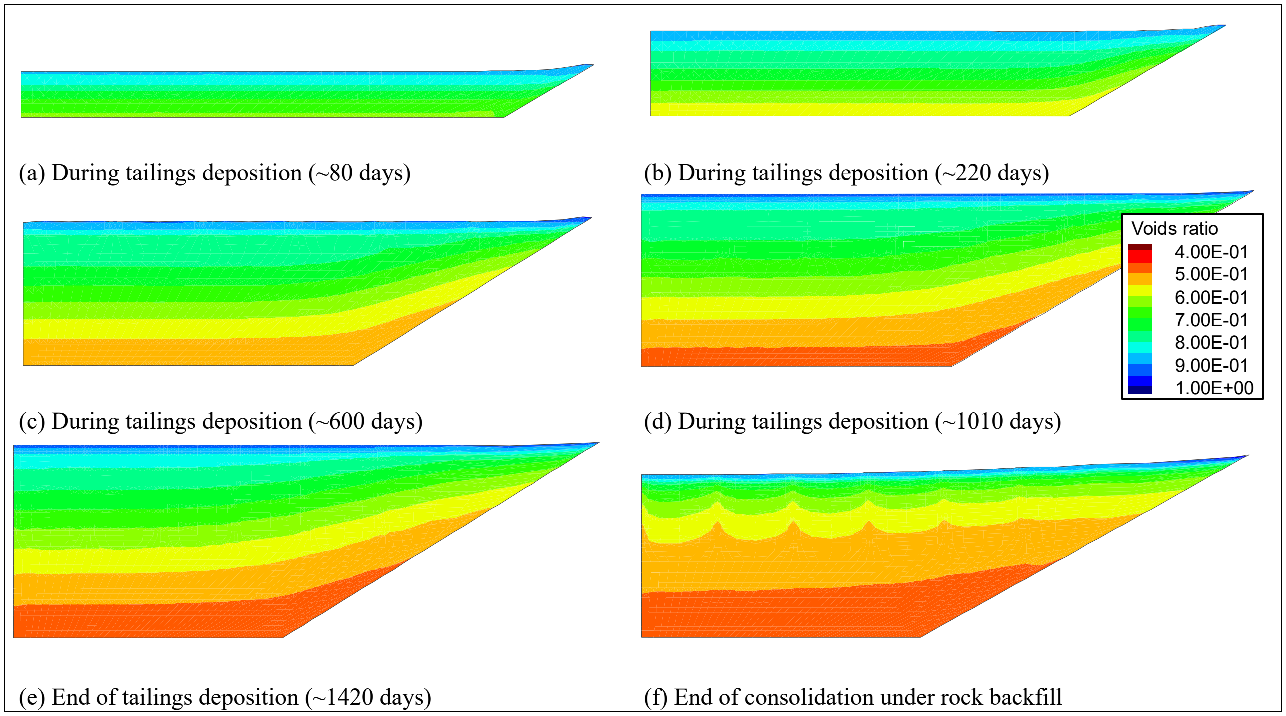


Figure 2. Contours of voids ratio with tailings deposition and consolidation under rock backfill.

REFERENCES

Barron, R.A. 1948. Consolidation of fine-grained soils by drain wells. *Trans. ASCE*, 113, 718-742.

Gibson, R.E. 1958. The progress of consolidation in clay layer increasing in thickness with time. *Géotechnique*, 8(4), 171–182.

Gjerapic, G., Johnson, J., Coffin, J. & Znidarcic, D. 2008. Determination of tailings impoundment capacity via finite-strain consolidation models, *GeoCongress 2008, ASCE*, pp. 798-805.

Hansbo, S. 1981. Consolidation of fine grained soils by prefabricated drains. *Proc., 10th Conf. Soil Mechanics and Foundation Engineering*, Vol. 3, 677-682.

Itasca Consulting Group, Inc. 2016. *FLAC – Fast Lagrangian Analysis of Continua, Ver. 8.0 User's Guide*. Minneapolis: Itasca.

Nguyen, B.H., Yun, D.H. & Kim, Y.T. 2018. An equivalent plane strain model of PVD-improved soft deposit. *Computers and Geotechnics*, 103 (2018) 32–42.

Tito, L.A.A. 2015. "*Numerical Evaluation of One-dimensional Large-Strain Consolidation of Mine Tailings*", thesis for the Degree of Master of Science, Colorado State University.

Townsend, F.C. & McVay, M.C. 1990. "SOA: Large Strain Consolidation Predictions", *Journal of Geotechnical Engineering*. 116(2), pp. 222-243.

Zhou H., Amodio A. & Boylan N. *Informed Mine Closure by Multi-dimensional Modelling of Tailings Deposition and Consolidation*.