Mine Closure 2019 - AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_rep/1915_23_Zhou

Informed mine closure by multi-dimensional modelling of tailings deposition and consolidation

H Zhou *Norwegian Geotechnical Institute, Australia*

A Amodio *Norwegian Geotechnical Institute, Australia*

N Boylan *Norwegian Geotechnical Institute, Australia*

Abstract

This paper introduces an advanced geotechnical numerical modelling approach, which can be used to simulate the gradual deposition and large-strain consolidation of tailings in a multi-dimensional space. The findings from the modelling can be used not only to inform planning and design at mine closure but also help the management of tailings impoundments. For example, the results can be used to determine the settlement of tailings with time and thus inform backfilling planning; or inform on the tailings settlement and thereby assist with the design of an effective drainage network to divert surface water.

Following a state-of-practice review of tailings consolidation modelling, the recently developed multi-dimensional modelling technique (the Norwegian Geotechnical Institute [NGI] model) is described in the paper, with validations against available analytical solutions and comparisons with commonly used predictions presented by Townsend & McVay (1990). An example of the application of the NGI model is presented to demonstrate its capability and performance in modelling a full-scale scenario.

The NGI modelling approach is built on commercially available specialised geotechnical modelling software, FLAC (and FLAC3D), through its embedded programming language, FISH. The NGI model extends FLAC's existing capability of large-strain consolidation calculation to simulate the gradual deposition process of the tailings. The deposition of the tailings slurry is divided into many discontinuous layers, and these layers are activated one after another from the bottom up. Activation of each new layer (on top of the existing tailings surface) is followed by a large-strain consolidation stage, with the consolidation time being determined as a function according to the volume of the layer and discharge history. Rock backfilling can be modelled in a similar fashion or can be customised.

A user-defined constitutive model (as part of the NGI model) has been developed to reproduce the key characteristics of the tailings during consolidation, including the variation of compressibility and permeability with reducing voids ratio. The consolidation of the tailings is modelled in a large-strain mode (i.e. the coordinates of the grid are updated frequently) in order to capture its effect on the consolidation behaviour and the deformation occurred prior to addition of a new layer.

The NGI model is also capable of performing complex three-dimensional problems accounting for varying consolidation boundary conditions, non-uniformity of the tailings material, and irregular pit geometries. As illustrated by the example application, this approach can be used to predict the development of tailing consolidation settlement with time, the amount of water expressed during consolidation, the capacity of the pit for tailings storage and the required amount of rock for backfilling.

Further development is ongoing in order to expand its modelling capability, such as prediction of increase in tailings strength with consolidation, modelling drying and consolidation of tailings, simulation of tailings dam construction process to improve prediction of tailings dam stability, and so forth.

Keywords: *numerical modelling, tailings, large strain, consolidation*

1 Introduction

In order to safely store the vast amount of tailings (mining waste) generated at some mining operations, large tailings impoundments are required. Reclamation of the tailings impoundments must be performed before closure of the mine can be completed. In addition, mine designers are often faced with the problem of predicting the capacity of impoundments for various production schedules and for different stages of mine development. Both tasks require an understanding of the physical and chemical processes of tailings following deposition in the impoundment. In particular, consolidation presents a challenge for the management of tailings. Consolidation will influence the overall capacity of the impoundment. Post-closure settlement and the expression of porewater over time are issues that should be considered during closure planning.

Tailings consolidation relates to the decrease in volume of deposited tailings slurry with time due to the discharge of porewater. High water content coupled with low permeability fine-grained mine tailings can yield large volume reduction and long elapsed time for completion of the consolidation. The consolidation process not only affects stability and storage capacity of tailings impoundment, and beach formation, but also poses the risk of long-term environmental impacts, for example, due to insufficient capacity for treating expressed waste water. Reliable prediction of tailings consolidation is therefore central to the planning and management of the mine throughout its entire life. Optimal mine closure plans can be produced by modelling a variety of mine closure scenarios. For example, different drainage designs (arrangements of wick drains) can be tested numerically to identify the most efficient one. In addition, required capacity of the waste water treatment facility can be predicted from the modelling. Similarly, different rock backfilling schemes can be modelled to find the most cost-effective one while meeting regulation requirements.

To better understand and manage tailings consolidation, many numerical prediction models have been developed and are used extensively by the industry. These models are considered an essential technical tool for designing the operational and post-closure phases of the tailings impoundment to meet with regulatory requirements. Accurate prediction of ground settlement at the surface of the tailings area can help backfilling design. Estimation of the water discharge rate from the consolidating tailings guides the appropriate planning of a water treatment facility.

The objective of this paper is to present an advanced numerical technique to simulate tailings deposition and consolidation in a multi-dimensional space. Benchmark examples have been selected from the literature to validate the modelling approach, followed by a case study to demonstrate the performance and capability of the modelling approach. Distinct from the majority of the currently used modelling approaches, the presented technique is built on commercial software and hence is powerful and highly portable. Its powerful capability includes multi-dimensional simulation, explicit modelling of various flow boundary conditions, pre-fabricated wick drains and a range of backfilling schemes.

2 State of the practice in tailings modelling

The behaviour of fine-grained tailings material in an impoundment can be primarily divided into three stages from the point of discharge: (i) flocculation, (ii) sedimentation, and (iii) consolidation (Imai 1981). This entire process is dominated by the consolidation stage, and therefore in practice, consolidation typically is the only process analysed (Znidarcic 1999). Tailings materials exhibit large-strain deformations with development of effective stress and deviate from the conventional small-strain assumption in that their properties (especially voids ratio, stiffness and permeability, which govern the consolidation response) continuously change with accumulating deformation. Thus, large-strain consolidation theories have been developed (e.g. Gibson et al. 1967) and numerical models, such as those adopted in Townsend & McVay (1990), have been successfully applied to predict consolidation behaviour of slurry materials including tailings. Governing constitutive relationships include the void ratio–effective stress relationship (e-σ'_v, also known as compressibility) and permeability–void ratio relationship (k-e). They are necessary to relate the coupled effects of increasing σ'_v on compressibility and permeability to solve the governing equations of large-strain consolidation (e.g. Gibson et al. 1967).

To date, many 1D 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 1D 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 1D 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 1D problems, the performance of the pseudo-3D approach will vary in modelling real full-scale problems, and very often case-specific calibration is required for the pseudo-3D approach. The disadvantages of the pseudo-3D approach are further magnified for the cases with irregular impoundment geometry, complex (e.g. non-vertical) drainage paths, nonhomogeneous distribution of tailings, etc. There is a need to develop real multi-dimensional modelling approaches in order to capture the features and complexities of common tailing consolidation cases.

3 NGI multi-dimensional tailings modelling approach

The developed NGI modelling approach is built on commercial specialised geotechnical software, FLAC (Itasca 2016). Due to the complexities of the problem, various extensions have been necessarily made, via the built-in FISH coding language in FLAC. In general, these modifications can be classified into two categories:

- *Constitutive modelling*, which captures the key features of the tailings' behaviour during large-strain consolidation.
- *Modelling procedure*, which can simulate gradual deposition of tailings into the impoundment.

These extensions are described in more details in the following sections. In addition, comprehensive outputs are made possible through the FISH coding, which provides valuable information for impoundment design and mine closure planning and management. This will be demonstrated by the example later.

3.1 Constitutive modelling of tailings material

The non-linear relationships of e-σ' and k-e, as discussed in Section 2, have been implemented by modifying the built-in Mohr–Coulomb model in FLAC (Itasca 2016). During the analysis, the value of the voids ratio for each element is first updated after every step of calculation according to the computed volumetric strain, followed by an update of the density, stiffness and permeability. Other parameters could also be updated if necessary (e.g. the strength parameters could also be updated with a predefined relationship with voids ratio in order to simulate its changes with consolidation, etc.).

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. This means for a system under load but in equilibrium, changing the elastic moduli will have no effect on the system since the subsequent incremental strains are zero. However, any increase in load, such as additional deposition of tailings, will generate incremental strains, which is governed by the updated elastic moduli (assuming elastic compression).

It is worth noting that the use of incremental algorithm in FLAC is an important feature for the present modelling, which enables the implementation of the non-linear e-σ' relationship.

3.2 Modelling of tailings' gradual deposition and consolidation

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). For ease of explanation, the modelling procedure is schematically depicted in Figure 1. As shown, each deposition stage (i.e. activation of one new layer above the existing tailings in the impoundment) is followed by a period of consolidation, with the consolidation time being computed according to the expected deposition rate and the initial volume of the activated layer. Depending on the tailings deposition rate relative to its consolidation properties, the thickness of each layer needs to be sufficiently small in order to achieve reliable prediction. If required, deposition of tailings of different properties can be modelled explicitly with this approach since it is built on multi-dimensional software, instead of 1D consolidation theory. This feature has been illustrated in the validation examples, that is, Scenario B and D of Townsend & McVay (1990) in Section 3.3. However, for the example in Section 4, the tailing material has been assumed homogeneous during deposition for ease of interpretation of the results.

Typically, the tailings are assumed to be deposited continuously in the impoundment while maintaining a horizontal surface. This is simulated exactly by the developed staged filling approach. As illustrated in Figure 1, for the newly activated layer, the top surface is purely horizontal while the bottom is the deformed surface of the existing tailings in the impoundment. This is an important feature for realistic modelling of the tailings gradual deposition and consolidation, since it allows different local deposition rates (i.e. deposition rate per unit area) across the pond. As can be expected, more tailings material will be deposited in the deep part of the impoundment where the tailings settle the most.

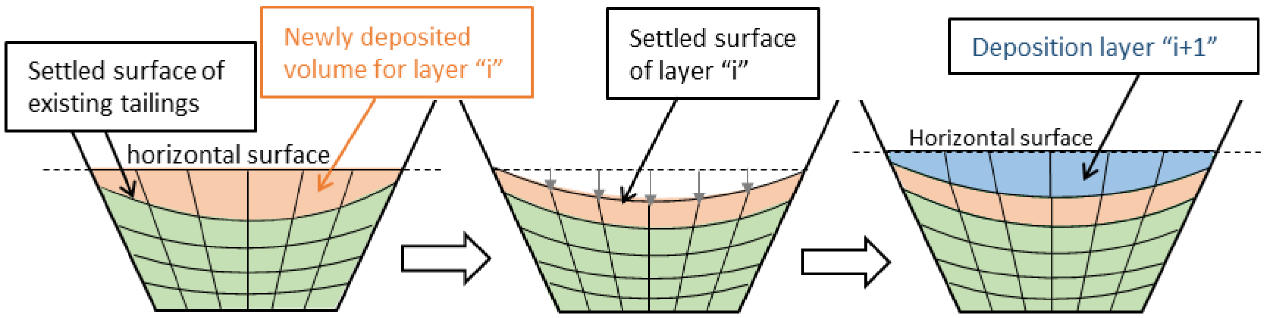


Figure 1 Deposition–consolidation sequence (layer-by-layer)

3.3 Validation of the NGI modelling approach

Various rigorous verifications and validations have been performed in the course of developing the modelling approach. For example, the gradual deposition modelling has been validated against the analytical solution developed by Gibson (1958). However, due to space limitations, only the comparison with the predictions presented in Townsend & McVay (1990) are reported in this paper. Note that Townsend & McVay (1990) summarised results of a prediction competition where nine teams of modellers predicted consolidation behaviour of four different waste clay disposal scenarios and the results are commonly used as a benchmark for the evaluation of numerical models of large-strain consolidation.

As shown below, the developed modelling approach achieves excellent results in comparison with predictions made by the participants. In doing so, greater confidence can be gained in applying the model to real complex multi-dimensional continuous deposition and large-strain consolidation problems.

3.3.1 Scenario A

Scenario A of Townsend & McVay (1990), as sketched in Figure 2(a), represents a quiescent consolidation of a waste pond that is instantaneously filled with phosphate tailings to an initial height of H = 9.6 m at a uniform initial void ratio, e_0, of 14.8 and a solid content, S_i, of 16%. Tailings were assumed to consolidate only under self-weight with drainage along the upper boundary and no flow along the bottom boundary and sides of the column.

Constitutive relationships for compressibility and permeability (i.e. e-σ'_v and k-e) were defined according to Townsend & McVay (1990) as:

$$e = 7.72{\sigma'}_v^{-0.22} \tag{1}$$

$$k = (0.2532E - 0.6)e^{4.65} \quad (2)$$

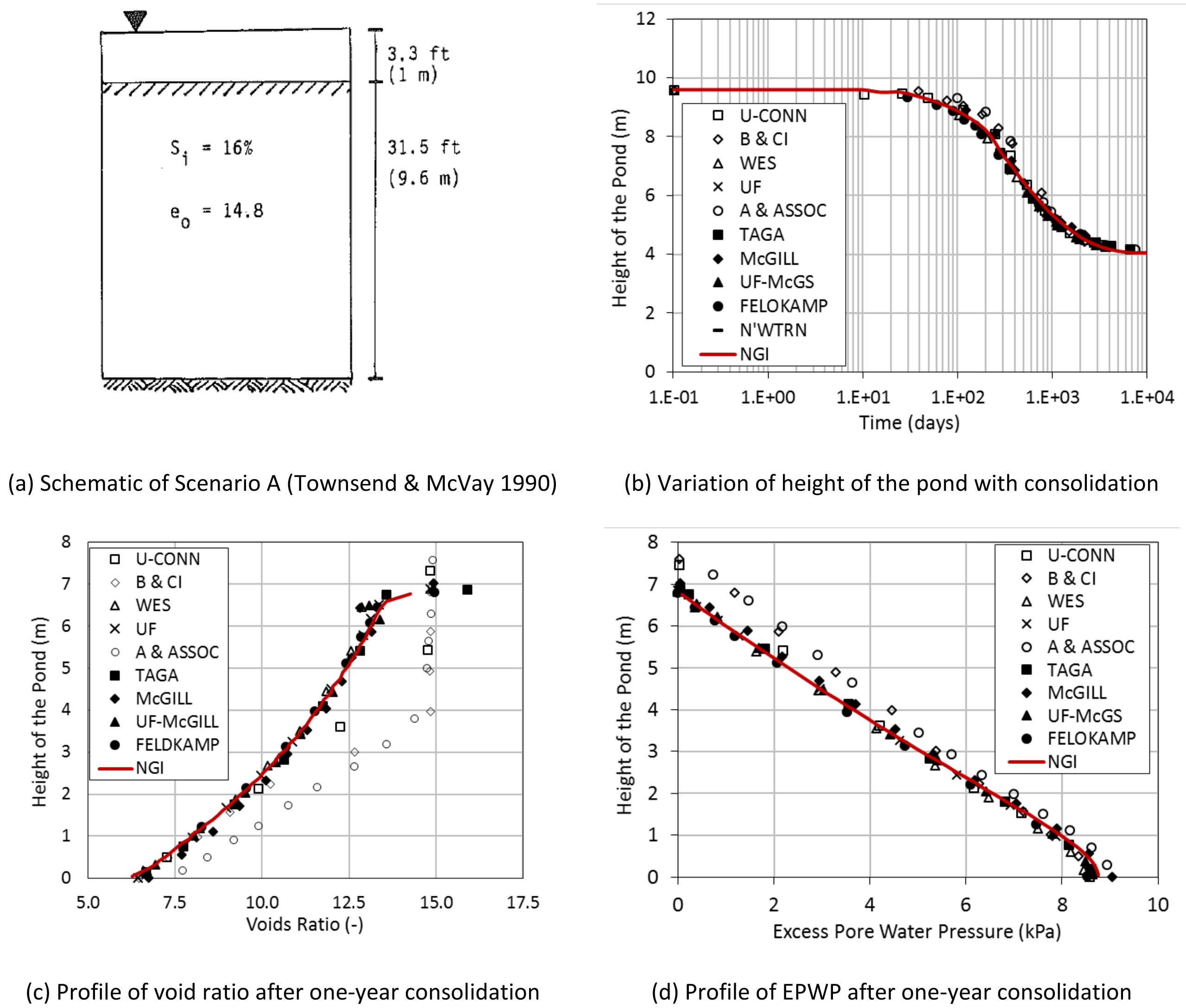
where:

σ_v' = effective vertical stress in kPa.

k = permeability in m/day.

The e-σ'$_v$ curve is also plotted in Figure 3 for the low stress level. It should be noted that for the present series of validation examples, it has been assumed that the deposition starts at σ'$_v$ = 0 and e = e_0, as specified. That is, the initial state (before consolidation) does not fall on the e-σ'$_v$ curve formulated by Equation 1. When consolidation starts (with increase in σ'$_v$), it follows an unloading–reloading line until it reaches the backbone e-σ'$_v$ curve when the stress is equal to the 'pre-consolidation pressure', σ_{pc}. The value of σ_{pc} varies with e_0, and the slope of the unloading–reloading line is assumed to be five times of the tangent of the point on the e-σ'$_v$ curve with σ'$_v$ = σ_{pc}. Figure 3 illustrates the relationship between e_0, σ_{pc}, the unloading–reloading line, and the e-σ'$_v$ curve.

The predicted results for this scenario are compared in Figure 2(b), in terms of the variation of the height of the pond with time; and in Figure 2(c) and Figure 2(d) respectively in terms of the profiles of the voids ratio and the excess porewater pressures (EPWPs) corresponding to one-year consolidation. As shown, the results agree with the majority of the predictions.



(a) Schematic of Scenario A (Townsend & McVay 1990)

(b) Variation of height of the pond with consolidation

(c) Profile of void ratio after one-year consolidation

(d) Profile of EPWP after one-year consolidation

Figure 2 Model performance by comparing with Scenario A predictions

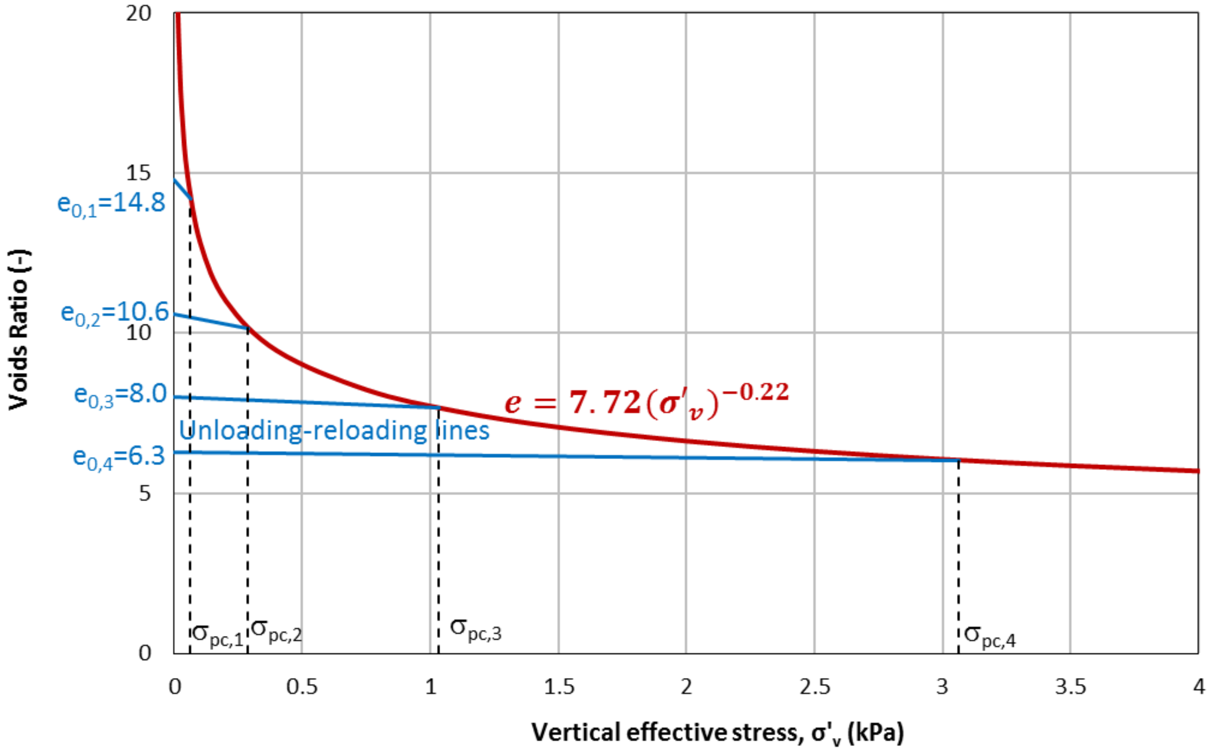


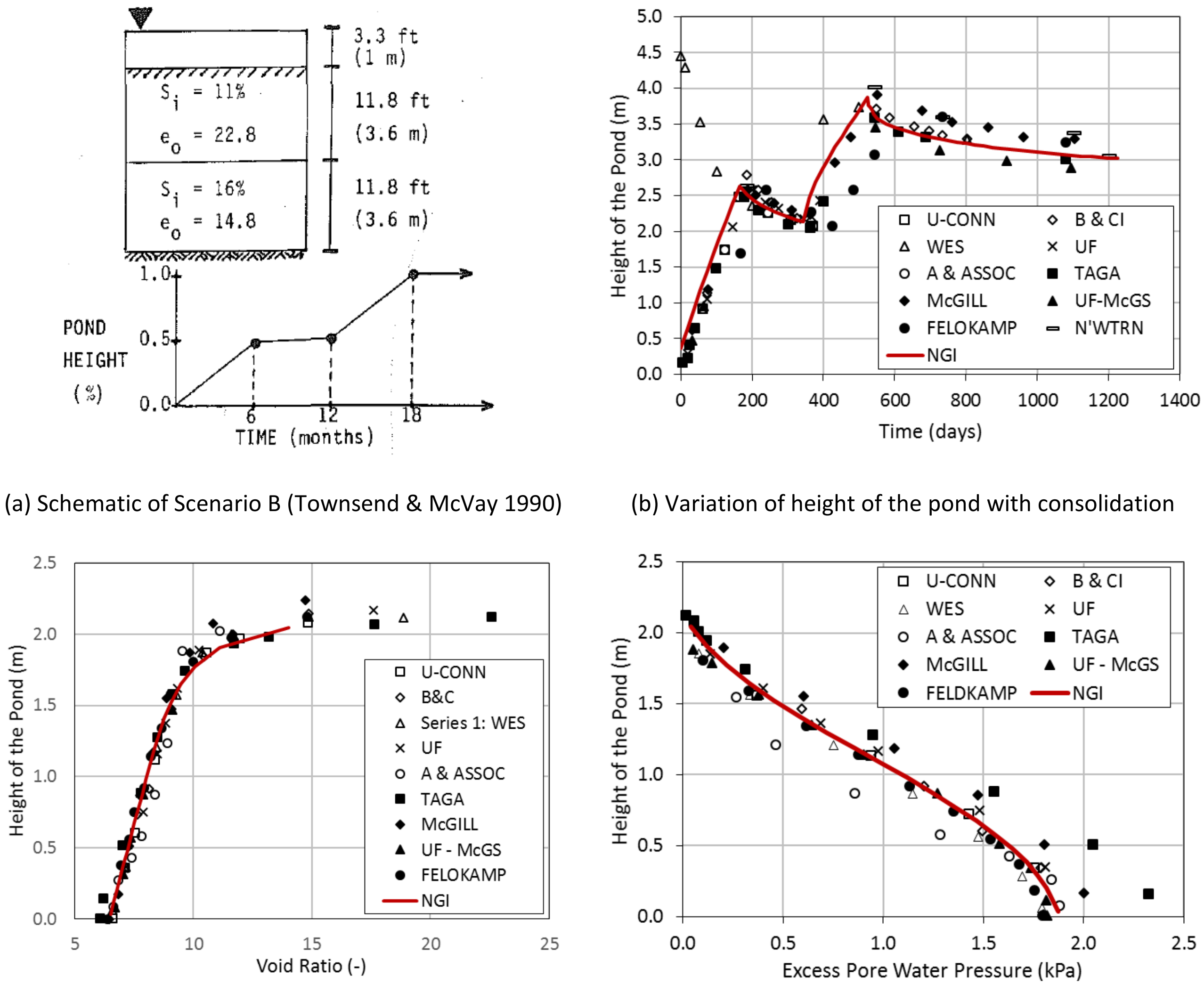
Figure 3 **Backbone compressibility curve and unloading–reloading lines for $\sigma'_v < \sigma_{pc}$**

3.3.2 Scenario B

Scenario B of Townsend & McVay (1990), as illustrated in Figure 4(a), represents a more complex but realistic deposition and consolidation condition than Scenario A, with two main differences as follows:

- The pond in Scenario B is filled gradually in two stages. Each deposition stage lasts six months and is intervened by a six-month consolidation stage.
- For each filling stage, the same type of material (i.e. following the same e-σ' and k-e constitutive relationships as formulated by Equations 1 and 2) is deposited, but starting at different initial voids ratios (Figure 3).

The prediction using the NGI model and other predictions in Townsend & McVay (1990) are compared in Figure 4(b) to Figure 4(d). Again, the good agreement of the NGI model with the majority of the predictions is positive.



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

(b) Variation of height of the pond with consolidation

(c) Profile of void ratio after one-year consolidation

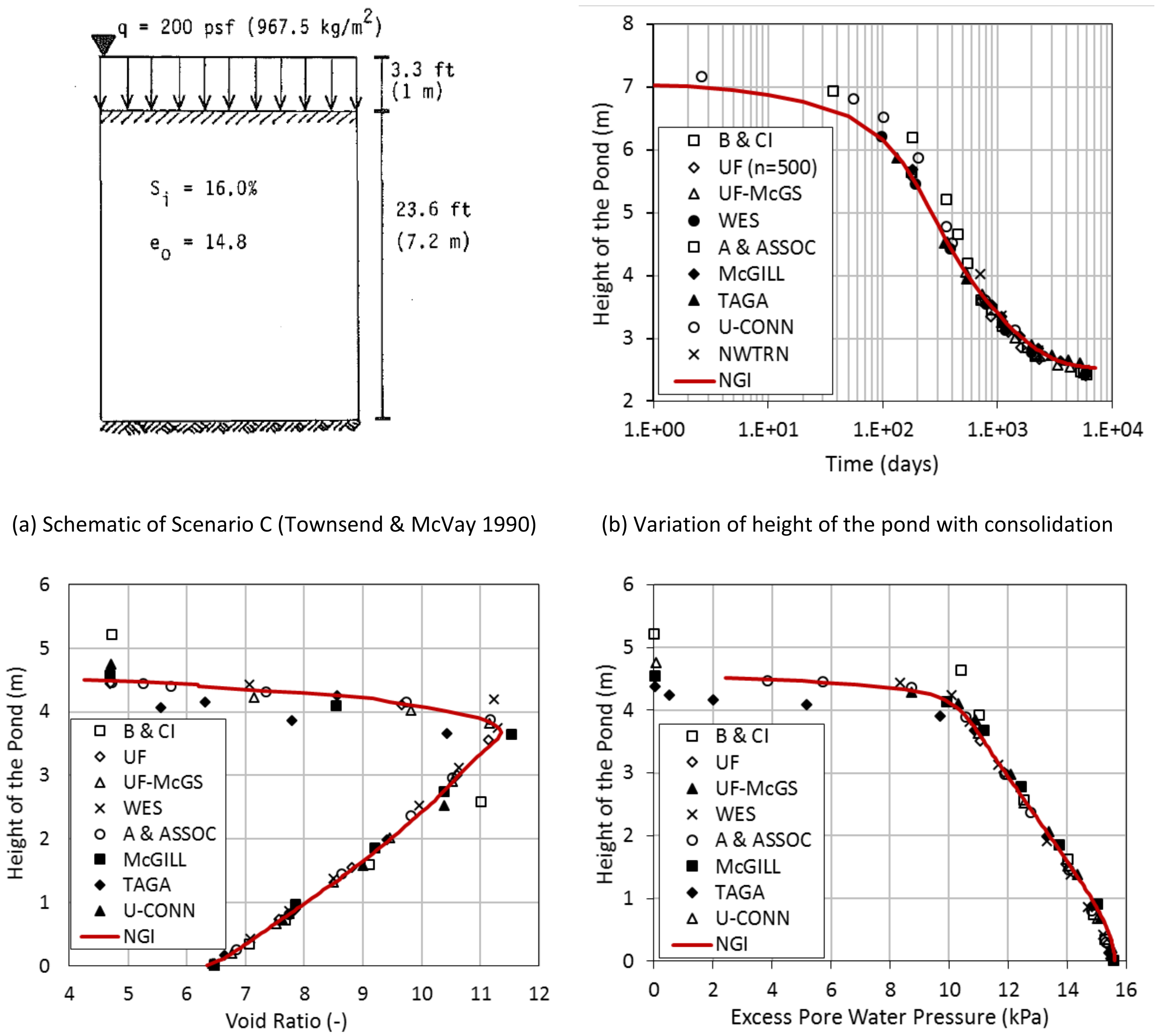
(d) Profile of EPWP after one-year consolidation

Figure 4 Model performance by comparing with Scenario B predictions

3.3.3 Scenario C

At face value, Scenario C is very similar to Scenario A, except the main difference is that it is capped with a uniform surcharge as shown in Figure 5(a). However, because of this, the profile of the voids ratio and EPWP after one-year consolidation is very different from that of Scenario A (Figure 2(c) versus Figure 5(c); Figure 2(d) versus Figure 5(d)), which also demonstrates the subtleness in modelling this scenario. The relatively more rapid consolidation of the top material (due to short drainage path) makes the top layer denser (smaller void ratio, e) and therefore less permeable, which affects the consolidation of the underlying material within the pond.

NGI's modelling approach successfully captures this aspect, and again agrees excellently with the majority of the predictions. It may be worth noting that the corresponding figures presented in Townsend & McVay (1990) are not consistent with the results summarised in the corresponding table in that paper. These have been corrected in Figure 5(b) to Figure 5(d), based on data presented in the corresponding proceedings for the symposium (University of Florida 1987).



(a) Schematic of Scenario C (Townsend & McVay 1990)

(b) Variation of height of the pond with consolidation

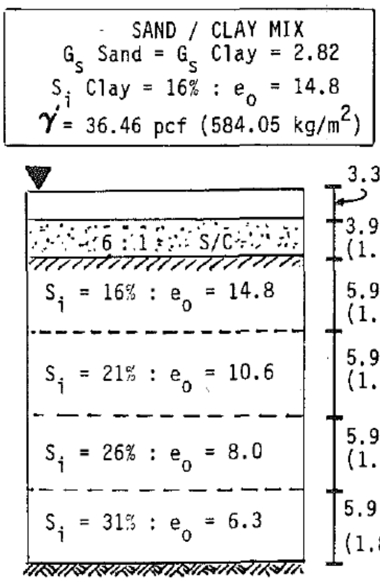
(c) Profile of void ratio after one-year consolidation

(d) Profile of EPWP after one-year consolidation

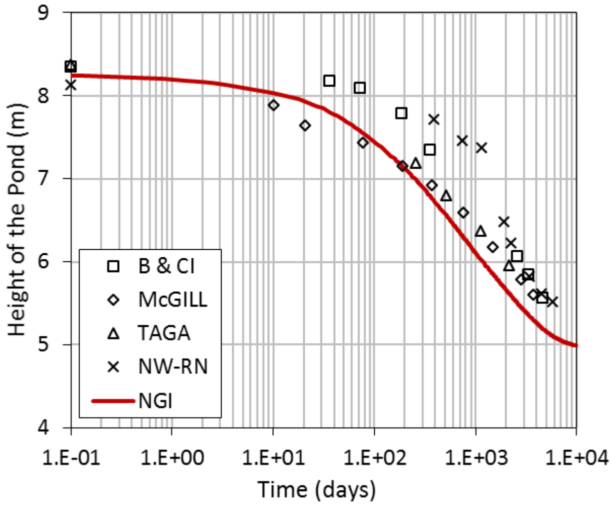
Figure 5 Model performance by comparing with Scenario C predictions

3.3.4 Scenario D

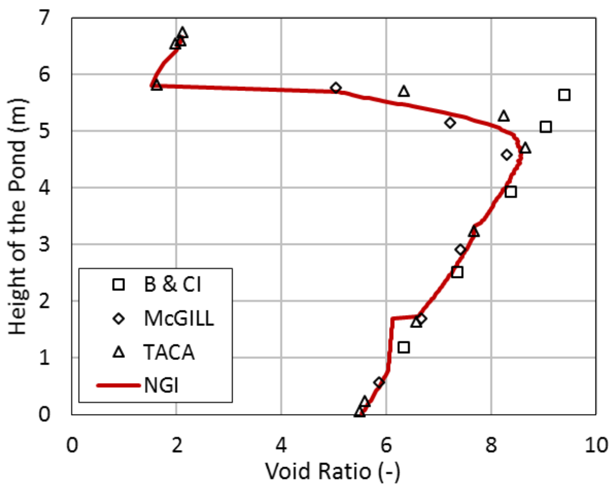
Scenario D, as illustrated in Figure 6(a), represents a quiescent consolidation of a non-uniform pond comprising four layers of materials, which follow the same backbone constitutive relationships as formulated by Equations 1 and 2 but start with different e_0, as annotated in Figure 6(a). The corresponding e-σ'_v relationships for each layer are shown in Figure 3. Different from Scenario C, the top is capped by a layer of sand/clay mix, with its properties being provided in Townsend & McVay (1990).



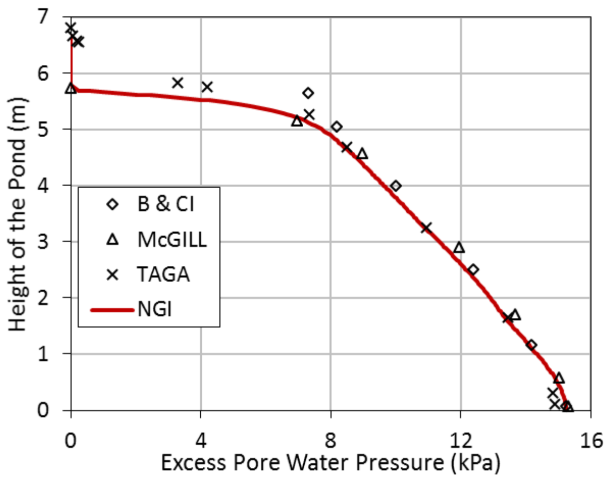
(a) Schematic of Scenario D (Townsend & McVay 1990)



(b) Variation of height of the pond with consolidation



(c) Profile of void ratio after one-year consolidation



(d) Profile of EPWP after one-year consolidation

Figure 6 Model performance by comparing with Scenario D predictions

The challenges in modelling this scenario are caused by the different initial voids ratios and distinct material properties between the clay and the sand/clay mixture for capping. The sand/clay mixture has a much larger permeability and relatively low compressibility than that of the underlying clay. It is likely that due to these complexities, only four predictions of the pond height and three predictions of the voids ratio and EPWP profiles have been presented in Townsend & McVay (1990), and are reproduced here in Figure 6(b) to Figure 6(d). On these figures, the prediction of the NGI model is also presented and again it compares well with the other predictions.

It is worth noting that for the top 0.8 m of the bottom layer, the value of σ_v' after one-year consolidation is less than σ_{pc} (Figure 3). Therefore, its state is on the unloading–reloading line and has not reached the backbone e-σ_v' curve. Accordingly, the value of e is calculated according to the unloading–reloading line and less than e_0 of 6.3. This explains the 'kink' present along the e profile after one-year consolidation (Figure 6(c)). If Figure 6(c) is examined in more detail, another minor 'kink' can be found in the layer above the bottom layer at just above 3 m, for the same reason.

4 Example – multi-dimensional modelling of tailings consolidation

A full-scale example is presented in the following sections to demonstrate the capability and performance of the developed modelling technique. For ease of interpretation of the modelling results, an axisymmetric model has been considered and the tailings is assumed to be discharged into the impoundment at a constant rate and to be evenly distributed over the entire surface of the impoundment. As mentioned in Section 2.2, typically tailings exhibit segregation in the deposition process, which can lead to spatial variability in the material properties. This effect is not considered in the present example, although the developed approach is fully portable to full 3D modelling by using FLAC3D (Itasca 2019) as the calculation platform.

4.1 Modelling details

In this example, an axisymmetric impoundment has been considered. The modelling procedure and discretised FLAC grid is shown in Figure 7, where the FLAC grid represents a unit-radian sector of the actual system comprising tailings, wick drains, rock backfill and the boundary of the impoundment. It should be noted that the grid shown in Figure 7 is pre-designed before the analysis actually starts, so it does not show the deformed grid, which will occur with the analysis. The deformed grid is shown in the figures presented later.

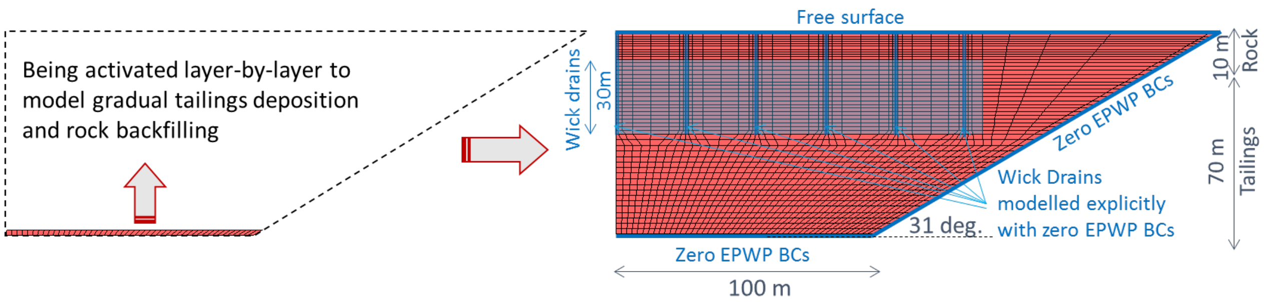


Figure 7 Modelling procedure: layer-by-layer activation of FLAC grid to model gradual deposition and consolidation of tailings and rock backfilling, with inclusion of wick drains

The geometry of the impoundment modelled effectively is an inverted cone frustum. As annotated in Figure 7, it has a base radius of 100 m, maximum tailings thickness of 70 m, and side slopes of 31˚. Rock has been backfilled on the top of the tailing as cap material.

Typical copper mine tailings material has been considered, which represents rapidly consolidating hard rock tailings typically encountered in mining practice (Tito 2015). According to Tito (2015), this material comprises approximately 60% fine-grained material (i.e. passing the No. 200 sieve) with D_{10} = 0.002 mm, and a specific gravity of 2.77. Dry density of the backfill rock is taken as 2.06 t/m^3, assuming minimal volume change throughout the entire process (by adopting very high stiffness in the modelling). The water level is assumed to be flush with the tailing top, namely the rock remains dry all the time.

A constant tailings deposition rate of 2 Mt per month was assumed in the simulations. For each activated layer, the time required for consolidation can be calculated based on the volume of the layer. Backfilling of rock at the top of the tailing as a part of mine closure is modelled in a way similar to gradual deposition of tailings, except that for the first rock layer where the thickness is maintained at 1 m uniformly across the top, instead of maintaining a horizontal top surface (as mentioned in Section 3.3). About one year has been assumed for completing the rock backfilling, a half year after the wick drains were installed.

Wick drains are installed one year after the tailings deposition is completed. They extend from the top of the tailings to 30 m below the tailing surface (Figure 7). The wick drains are modelled with zero EPWP boundary conditions (BCs) combined with an 'equivalent' permeability. As shown in Figure 7, the grid is purposely designed for specifying zero EPWP BCs at the wick drain locations. The 'equivalent' permeability has been estimated based on our experience and research findings in the public domain (e.g. Barron 1948; Hansbo 1981; Nguyen et al. 2018).

Zero EPWPs are assumed along the base and wall of the impoundment, considering the fact that the base is connected to a decant pond to maintain the hydrostatic pressure, and the surrounding rock near the sidewall is permeable. A bonded interface is assumed between the tailings and sidewall and base of the impoundment, although any intermediate interface conditions (between smooth and rough) can be modelled if necessary.

4.2 Results and discussion

Some of the results are presented in the following sub-sections to demonstrate the performance of the modelling approach, and the information can be extracted from the model.

4.2.1 Overall results

The change in the elevation of tailings surface during deposition, rock backfilling and consolidation stages are shown in Figure 8. Since a fully bonded interface has been assumed between the tailings and the side of the impoundment, as mentioned in Section 4.1, the elevation at the edge rises during deposition and remains unchanged during consolidation. In the middle, the surface drops gradually during consolidation, as expected.

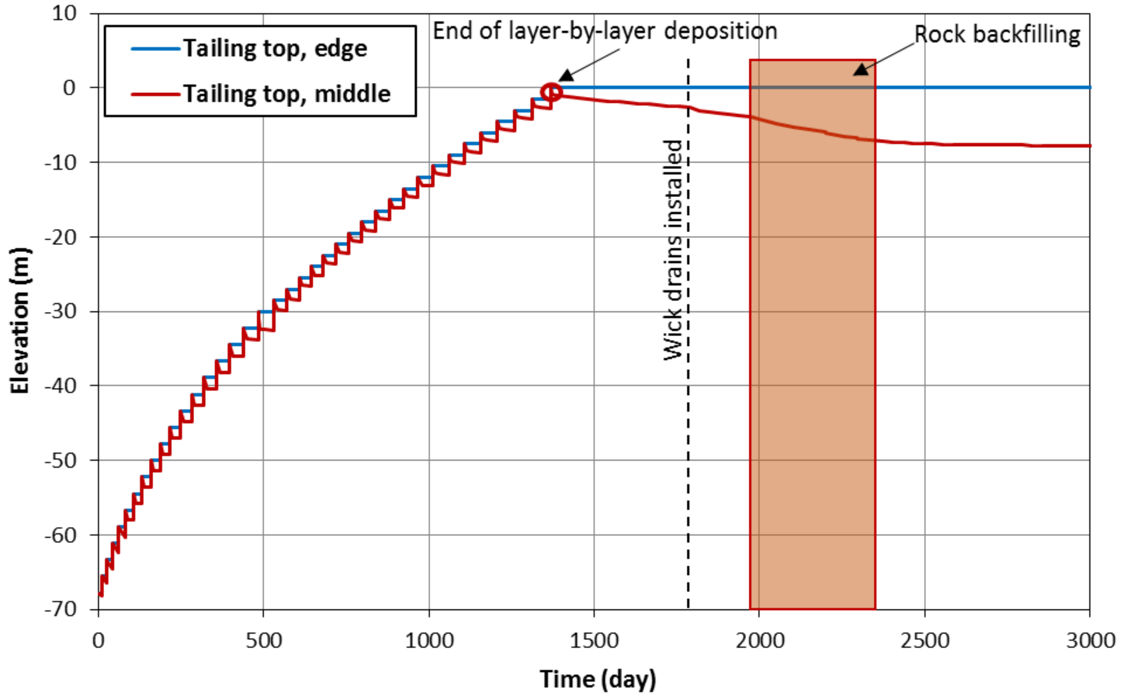


Figure 8 Variation in the elevation of tailings surface during deposition, rock backfilling and consolidation

The reduction in the tailings volume from the end of deposition to end of consolidation is shown in Figure 9, as well as the volumes of the water flowing to the top and to the side and bottom of the impoundment. At the earlier stage of consolidation, the rate of tailings settlement and water discharge is relatively fast due to higher permeability. Inclusion of wick drains speeds the water discharge from the top, while rock backfilling speeds water discharge both from the top and from the side and bottom of the impoundment. For this case, about 80% of the porewater is discharged from the top of the tailings.

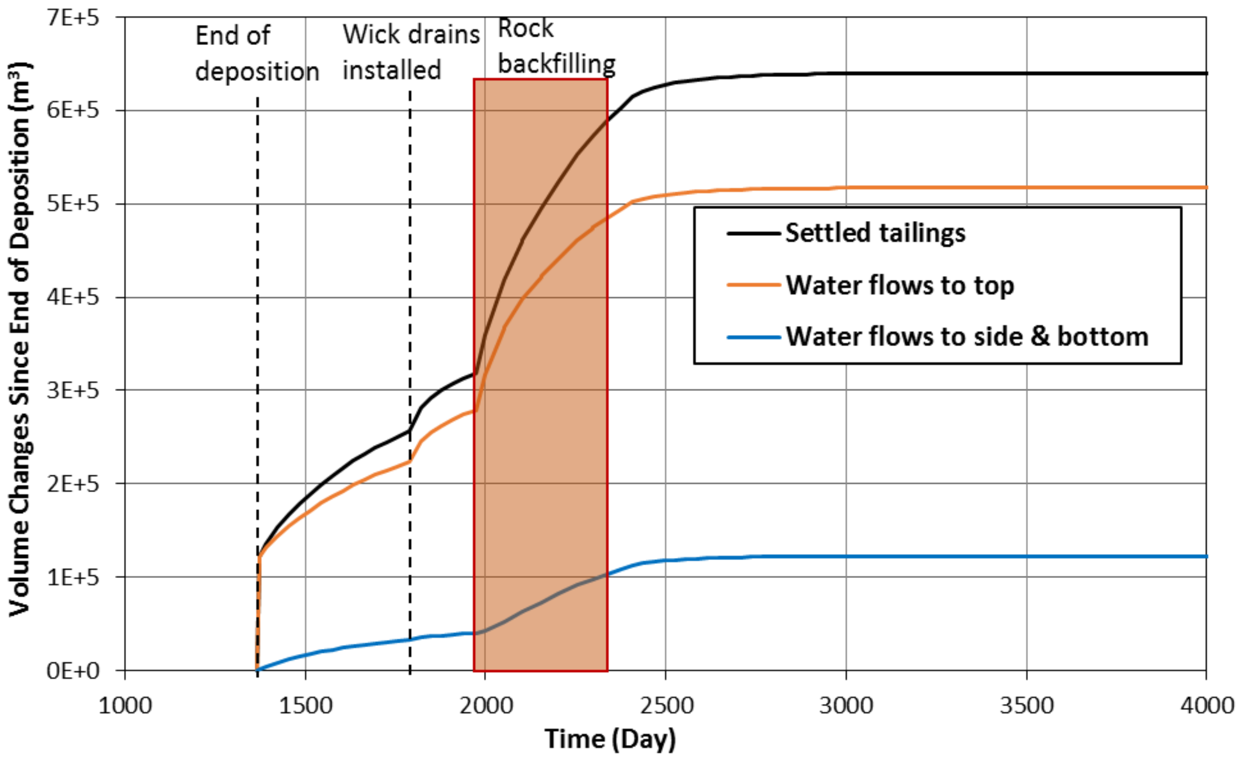


Figure 9 Volumetric reduction of the tailings, and volumes of water flowing to the top and to the side & bottom from the end of tailings deposition

The comparison between the tailings volume actually being discharged into the impoundment and the geometric volume of the impoundment calculated based on the elevation of the tailings is shown in Figure 10. Due to the consolidation occurring simultaneously with deposition, the actual capacity of the impoundment is significantly bigger than its geometric volume; and in this case, the ratio is about 1.6.

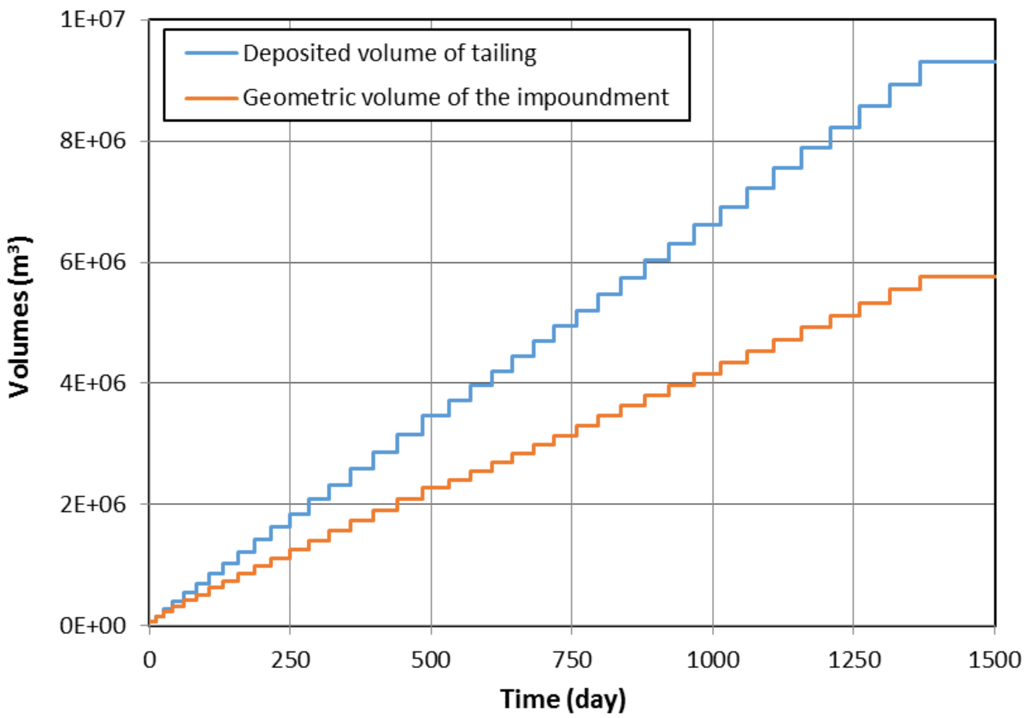
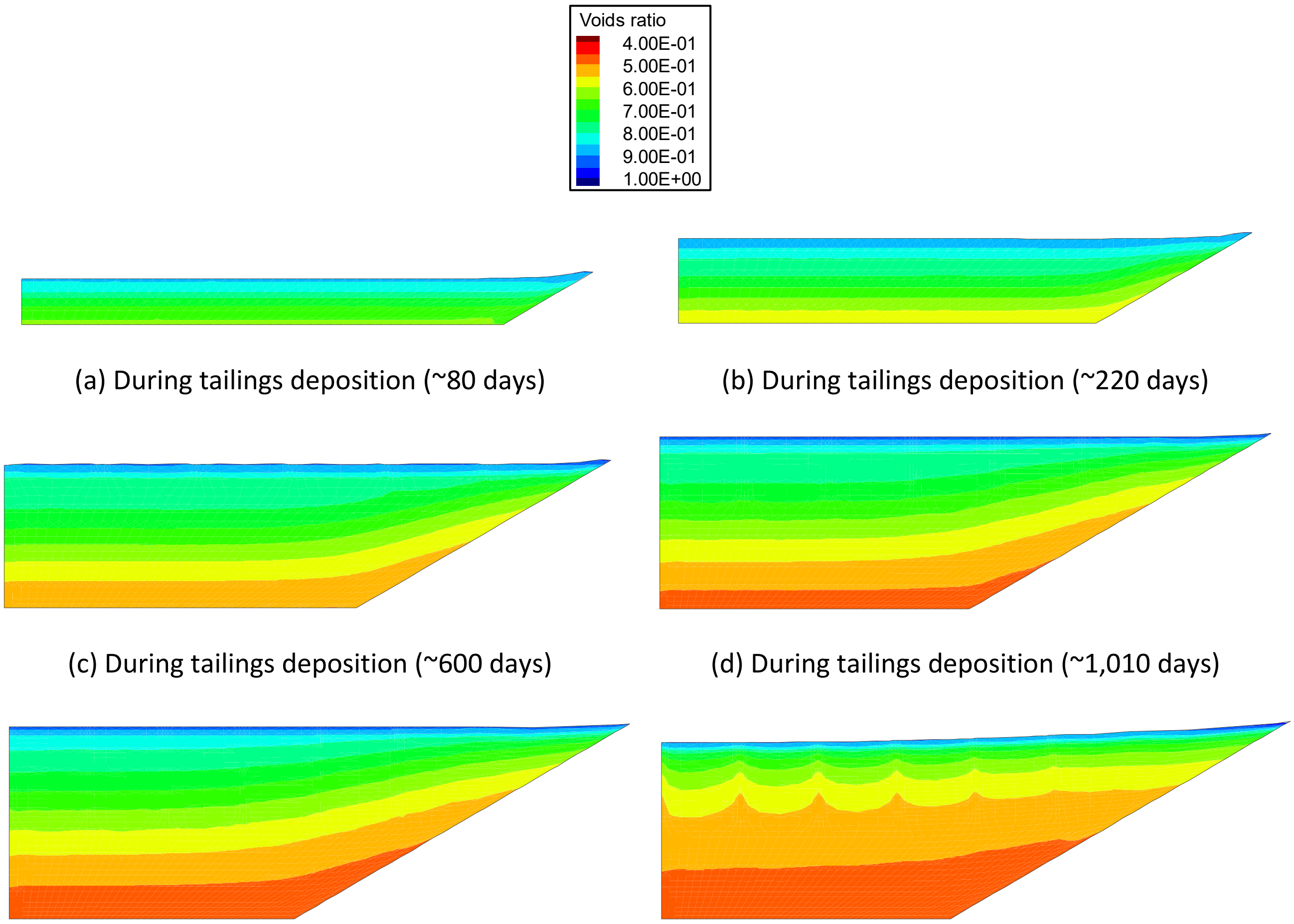


Figure 10 Comparison between deposited tailings volume and geometric volume

4.2.2 Selected results at stages of deposition and consolidation

The variation of tailings voids ratio with different deposition and consolidation stages is plotted in Figure 11, which illustrates the modelling process of the gradual deposition of the tailings and change in soil states. In the process, the voids ratio reduces gradually from the bottom of the impoundment. The wavy distribution of the voids ratio in Figure 11(f) is due to the inclusion of wick drains, which speed up dissipation of EPWPs locally and hence reduce the voids ratio.



(a) During tailings deposition (~80 days)

(b) During tailings deposition (~220 days)

(c) During tailings deposition (~600 days)

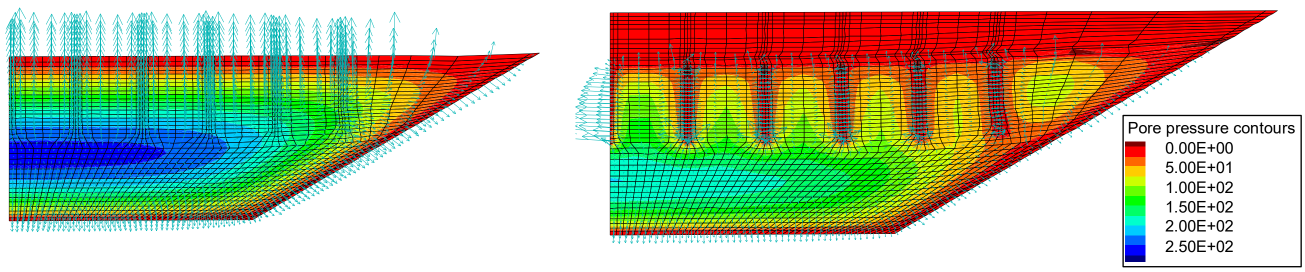
(d) During tailings deposition (~1,010 days)

(e) End of tailings deposition (~1,420 days)

(f) End of consolidation under rock backfill

Figure 11 Contours of voids ratio with tailings deposition and consolidation under rock backfill

The contour of EPWPs overlain by flow vectors is plotted in Figure 12(a) and Figure 12(b), respectively corresponding to the end of tailings deposition and the end of rock backfilling. In both figures, the highest EPWP occurs in the middle and below the wick drains since the bottom and side of the impoundment is assumed permeable. The wick drains are installed before rock backfilling and its effect can be seen in Figure 12(b) from the flow vectors. These wick drains contribute considerably to the water flowing to the top of the tailings. In addition, as can be seen from Figure 12(a), the flow vectors are longer in the middle and near the surface, since the EPWP gradient is greater and the material is looser compared with elsewhere. These two reasons explain why there is much more water flowing to the top than to the side and bottom (Figure 8(c)).

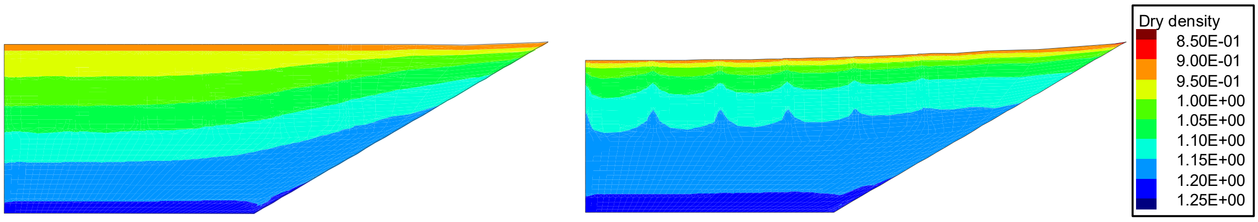


(a) At the end of tailings deposition

(b) At the end of rock backfilling (with wick drains)

Figure 12 Contour of EPWPs overlain by flow vectors

The distributions of dry density are shown in Figure 13, calculated based on the voids ratio as shown in Figure 11.



(a) At the end of tailings deposition

(b) At the end of consolidation under rock (showing tailings only)

Figure 13 Contour of dry density

5 Conclusion

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

- Modelling of full-scale tailings consolidation is often performed using 1D models or a variant of these models referred to as 'pseudo-3D'. To model the gradual deposition and large-strain consolidation of tailings using these approaches requires approximations, and in some cases these models are not capable of capturing key features of the processes involved.
- There is a need to develop full-scale multi-dimensional modelling approaches to improve the prediction of tailings consolidation. A better prediction of tailings consolidation can improve impoundment management and inform mine closure planning and management.
- The developed NGI modelling approach has shown to provide excellent predictions. Since all the key aspects can be modelled explicitly during the process, this approach is believed to perform at a consistently reliable level, regardless of the complexity of the problem.
- Since the modelling approach is built on commercial software, 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 maximise its functionality, such as prediction of the increase in tailings strength with consolidation, modelling drying and consolidation of tailings and simulation of tailings dam construction process to improve prediction of tailings dam stability.

Acknowledgement

The authors thank Itasca for the technical support and discussion/clarification on FLAC.

References

Barron, RA 1948, 'Consolidation of fine-grained soils by drain wells', *Transactions of the ASCE*, vol. 113, iss. 1, pp. 718–742.

Gibson, RE 1958, 'The progress of consolidation in clay layer increasing in thickness with time', *Géotechnique*, vol. 8, no. 4, pp. 171–182, https://doi.org/10.1680/geot.1958.8.4.171

Gibson, RE, England, GL & Hussey, MJL 1967, 'The theory of one-dimensional consolidation of saturated clays', *Géotechnique*, vol. 17, no. 3, pp. 261–273, https://doi.org/10.1680/geot.1967.17.3.261

Gjerapic, G, Johnson, J, Coffin, J & Znidarcic, D 2008, 'Determination of tailings impoundment capacity via finite-strain consolidation models', in AN Alshawabkeh, KR Reddy & MV Khire (eds), *Proceedings of GeoCongress 2008*, American Society Of Civil Engineers, Reston, pp. 798–805, https://doi.org/10.1061/40972(311)99

Hansbo, S 1981, 'Consolidation of fine grained soils by prefabricated drains', *Proceedings of the 10th Conference on Soil Mechanics and Foundation Engineering*, vol. 3, A.A. Balkema, Rotterdam, pp. 677–682.

Imai, G 1981, 'Experimental studies on sedimentation mechanism and sediment formation of clay materials', *Soils and Foundations*, vol. 21, no. 1, pp. 7–20, https://doi.org/10.3208/sandf1972.21.7

Itasca 2016, *FLAC 8.0 (Fast Lagrangian Analysis of Continua) User Manual*, Itasca Consulting Group, Inc., Minneapolis.

Itasca 2019, *FLAC3D 7.0 (Fast Lagrangian Analysis of Continua in 3 Dimensions) User Manual*, Itasca Consulting Group, Inc., Minneapolis.

Nguyen, B-P, Yun, D-H & Kim, Y-T 2018, 'An equivalent plane strain model of PVD-improved soft deposit', *Computers and Geotechnics*, vol. 103, pp. 32–42, https://doi.org/10.1016/j.compgeo.2018.07.004

Tito, LAA 2015, *Numerical Evaluation of One-Dimensional Large-Strain Consolidation of Mine Tailings*, master's thesis, Colorado State University, Fort Collins.

Townsend, FC & McVay, MC 1990, 'SOA: Large strain consolidation predictions', *Journal of Geotechnical Engineering*, vol. 116, no. 2, pp. 222–243, https://doi.org/10.1061/(ASCE)0733-9410(1990)116:2(222)

University of Florida 1987, *Symposium on Consolidation and Disposal of Phosphatic and Other Waste Clays*, Department of Civil Engineering, University of Florida, Gainesville.

Znidarcic, D 1999, 'Predicting the behavior of disposed dredging soils', in FBJ Barends, J Lindenberg, HJ Luger, L de Quelerij & A Verruijt (eds), *Geotechnical Engineering for Transportation Infrastructure: Theory and Practice, Planning and Design, Construction and Maintenance*, A.A. Balkema, Rotterdam, pp. 877–886.