

Pseudo 3-D deposition and large-strain consolidation modeling of tailings deep deposits

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ABSTRACT

The design of deep deposits requires the numerical modeling of large-strain consolidation to represent the release of water with time. Such numerical modeling in the state of practice has traditionally involved the practice of running a single 1-D large-strain consolidation numerical model at the center of the deposit and inferring long-term performance from such numerical modeling. The difficulties with such a methodology are that the 3-D effects of depositing in a tailings facility are not fully considered. Full 3-D numerical modeling of the large-strain consolidation process has been performed however it remains technically challenging to model the deposition process in a 3-D model. Therefore the present paper presents using the pseudo 3-D methodology and coupling it with a depositional model in order to obtain an accounting for the 3-D effects of such a numerical analysis. The deposition process is represented through a 3-D methodology to determine the true surface of the tailings. The consolidation process is modeled through a discretization of the consolidation models into a series of 1-D numerical models such as to represent the final surface as a 3-D representation of the consolidation models vs. time as well as the tailings volumes as a function of time. The methodology is outlined in the paper and its utilization in a typical case study is examined.

1 INTRODUCTION

Accurately modeling the combined processes of tailings deposition and large-strain consolidation in a deep deposit is challenging. By optimizing the design of the tailings facility the cost benefits and profit increases gained by operators can be substantial.

Several methodologies for modeling the concurrent deposition and consolidation of tailings have been implemented with varying degrees of success. One-dimensional models can accurately describe the consolidation process including the non-linear nature of the material properties but they fail to represent the three-dimensional geometric features of the tailings facility. On the other hand, three-dimensional models represent the geometry of the facility well but modeling the depositional process can be challenging.

A pseudo 3-D methodology (Coffin, 2010) that addresses these issues is described and a case study that demonstrates its use in the form of a numerical software package will be presented.

2 DEPOSITIONAL SCENARIO

The timeline of a pseudo 3-D analysis is described in terms of a set of sequential stages. Each stage has a time duration, an action, and if applicable a filling rate and material. The sum of the individual stage durations defines the total simulation time. The stage action can be either deposition or quiescent. If the stage action is deposition then the filling rate and material type to be deposited must be specified. This means that each stage can have a different filling rate, different material, and different depositional surface shape. The depositional surface can have one of the following three shapes:

1. Constant elevation
2. Elevations calculated based on a user-defined slope radiating from the deposition point
3. Elevations defined by a user-imported surface in the form of a grid or triangulated mesh

For a deposition stage action, the depositional surface is calculated based on the user-chosen shape, the filling rate of material, and the time duration for the given stage. Together the filling rate and deposition time are multiplied to calculate the volume of material to be deposited during the stage.

For the user-defined slope shape a sequence of deposition points is used to simulate deposition from specific locations on the perimeter of the depositional area. A conical shape with slope equal to the user-defined value is radiated outward from each deposition point until the surface covers the entire depositional area. Currently, the deposition points are assumed to all have the same slope and equal filling rates for a given stage. Therefore, the volume of material deposited for a given stage is divided equally between all of the deposition points. Also, deposition is assumed to be simultaneous from all deposition points for the duration of the stage. Deposition points are not applicable to the constant elevation and user-imported surface shapes.

The user-chosen shape of the depositional surface and the deposition points are used to fully define all of the elevations in the depositional surface. An iterative algorithm is used to search for the elevation of the depositional surface such that the volume enclosed by the depositional surface, the ground surface, and the depositional boundary is equal to the volume of material to be deposited. The layer thicknesses over time for each 1-D numerical model are determined by interpolating the elevation on each depositional surface at the 1-D numerical model's location.

3 PSEUDO-3D METHODOLOGY

The following methodology is described based on its current implementation in SoilVision Systems Ltd. Tailings Management Planner Software (SoilVision TMP software). This software is currently under development but able to be run for consulting project analysis.

There are several geometric components that form the basis for a pseudo 3-D analysis of a tailings management facility (TMF). First, a ground surface in the form of a grid or triangulated mesh is used to represent the topology of the TMF prior to the deposition of tailings. Second, a depositional boundary is used to define the extents of the area where deposition is to occur. These two components define the lower and outer bounds of the depositional area. The upper bound is defined by the shape of the depositional surface. The depositional surface may have a constant elevation, elevations calculated based on a user-defined slope, or have elevations defined by a user-imported surface in the form of a grid or triangulated mesh. Sample geometry with each of the geometric components present is shown in Figure 1.

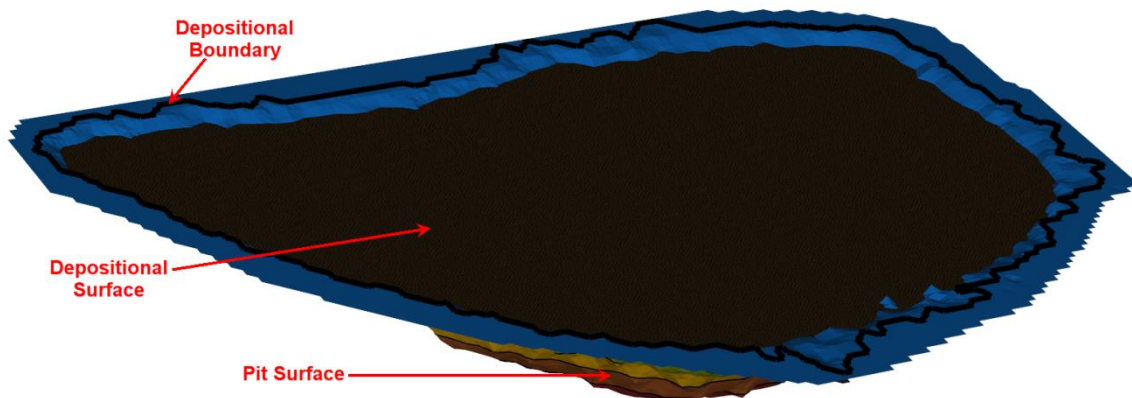


Figure 1: Pseudo 3-D analysis geometry showing ground surface, depositional boundary, and depositional surface

Pseudo 3-D numerical modeling divides the bounding box of the depositional boundary into a grid of 1-D numerical models. Each “cell” of the grid represents a single isolated 1-D large-

strain consolidation numerical model. Only cells that lie within the depositional boundary are included in the analysis (Figure 2). SoilVision TMP software utilizes the SVFLUX GT / SVSOLID GT 1-D large strain consolidation software to solve each large-strain numerical model (SoilVision Systems Ltd, 2015). This product has been rigorously tested and verified on many consolidation models (SVFLUX™/SVSOLID™ Large-strain consolidation verification manual).

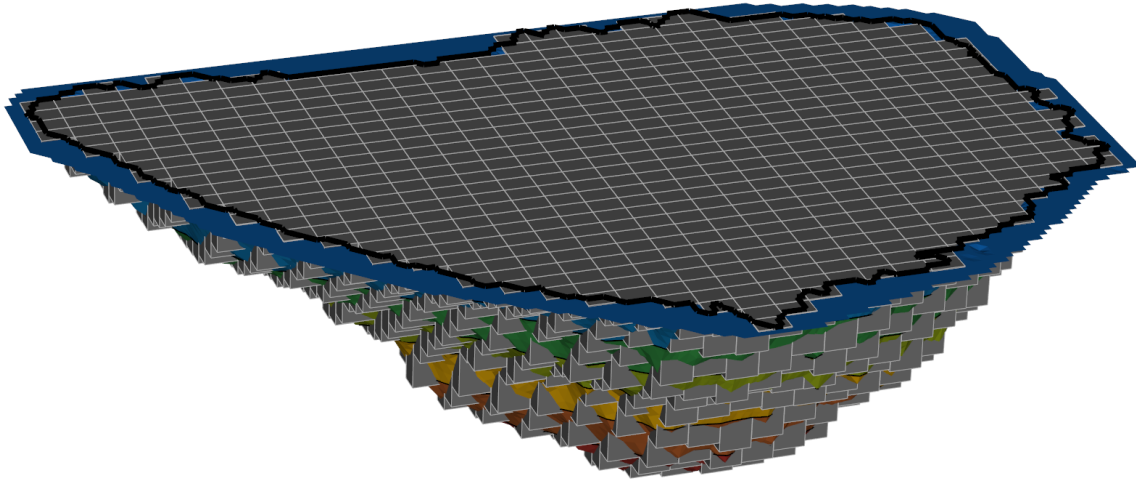


Figure 2: Depositional boundary divided into grid of columns

The individual 1-D numerical models are scheduled based on the depositional layering scenario for each model and based on their location in the 3-D deposit. In other words, the layer thicknesses and their construction times required by the 1-D numerical model are calculated based on the location of the column in the deposit and the depositional surface at a given point in time.

Calculations for computing the volume of material in the facility are based on the sum of the volumes of each individual 1-D column. Specifically, the top of each column is the interpolated elevation on the depositional surface at the column's center points. The bottom of each column is the interpolated elevation on the tailings ground surface at the column's center point. The area of the column's top flat surface is multiplied by the height of the column to give a volume for the column. The total volume is calculated as the sum of the individual column volumes. The accuracy of the volume calculations is dependent on the number of column used in the analysis.

Upon completion of the consolidation analysis the layer elevations at every stage for each column are stored. For each stage in the simulation the relevant layers for each column are displayed creating a 3-D surface effect. Also, for each stage the volume of tailings in the facility is calculated and displayed.

The pseudo 3-D analysis is performed to provide an indication of the final topology of the deposit at various future times. The simulation includes the effect of consolidation on the pseudo 3-D columns. In this modeling methodology each of the 1-D numerical models only considers vertical flow and stress distribution. Lateral flows or stresses between the columns are not considered. Pseudo 3-D analysis is ideally suited for facilities with a high horizontal to vertical ratio in their geometry. In a full 3-D analysis it is sometimes difficult to get sufficient resolution in the vertical direction in the finite element mesh to maintain solver stability.

Pseudo-3D analysis alleviates this problem.

3.1 Discretization Errors

As with any numerical simulation there are errors associated with approximations made in the simulation. In the presented pseudo 3-D methodology, the discretization of the tailings facility into a grid of columns introduces the largest source of error in the numerical simulation. This error in approximating the 3-D geometry of the tailings facility presents itself as an error in the volume calculations. Increasing the number of columns in the pseudo 3-D analysis will decrease this error because the 3-D aspects of the tailings facility geometry will be more closely approximated.

The user can control the error associated with the volume calculations using one of two methods:

1. Specify a relative and absolute error and have the program determine the number of columns required to meet the error requirements
2. Specify the number of columns and have the program report the error associated with the chosen column discretization

3.2 Large-Scale Computations

The number of columns in the pseudo 3-D analysis required to accurately represent the depositional surface topology is dependent on the size of the depositional area. It is common for the total number of columns to be in the thousands and tens of thousands. The computation time to analyze a single column with consolidation over a period of 100 years can be several minutes to several hours. Analyzing thousands of these models sequentially could potentially result in a pseudo 3-D analysis time in terms of weeks. Because no lateral effects between columns are considered each column's analysis is completely independent of all other columns. This means a pseudo 3-D analysis is very well suited for parallel computations.

Solution of a pseudo 3-D analysis involves the following three phases:

1. Computation of initial depositional surfaces
2. Consolidation of each 1-D numerical model
3. Assembling the final consolidation surfaces back into the 3D model

The step involving the most computational effort is Step 2. Each consolidation numerical model can be solved independently. The time savings is therefore highly dependent upon the number of cores available for the computations. For example, if a pseudo 3-D analysis on a machine with a single core takes 1 hour then the same analysis on a machine with 2 cores will take roughly half an hour. The time savings is much less for analyses where the 1-D numerical models solve in a matter of a few seconds.

4 NUMERICAL SOFTWARE

Little is available in terms of software packages that model the combined deposition and consolidation processes for a tailings facility. Designs are often based on 1-D consolidation theory with a single column used to model the behavior of the entire 3-D geometry of the tailings facility. In addition, these designs do not account for depositional scenarios other than a perfectly horizontal tailings surface.

The current approach presented in this paper improves upon these previous efforts in the following ways (Table 1).

Table 1: Feature listing of SoilVision TMP Software

Feature	Details
Depositional scenarios	Horizontal, sloped, user-defined, and based on deposition points surfaces
Variable filling rates	Each stage can have a different filling rate
Material property types	Many compression and conductivity curves to choose from
Unsaturated Analysis	Includes climatic analysis
No. of filling materials Filling curve	Each stage can have a different material Automatically calculated
Error in volume vs time calculations	Can be controlled by user-specified error input values
Parallel Computing	User can set the number of computing cores to be used to solve the consolidation models
Visualization of input/output	3-D visualization including elevation contouring of the tailings facility geometry at all stages in the simulation. 2-D graphs of volume vs time and water volume expelled vs time

5 CASE STUDY

The following example illustrates a sample pseudo-3D analysis with saturated large-strain consolidation solved by the SoilVision TMP software over a period of 200 years. The TMF ground surface geometry from a generic example is shown in Figure 3 and the associated filling curve is shown in

Figure 4. The embankment elevation surrounding the pit is constant at 53.6 m forming the upper limit on the storage capacity. From the filling curve the capacity of the pit at 53 m is roughly 28

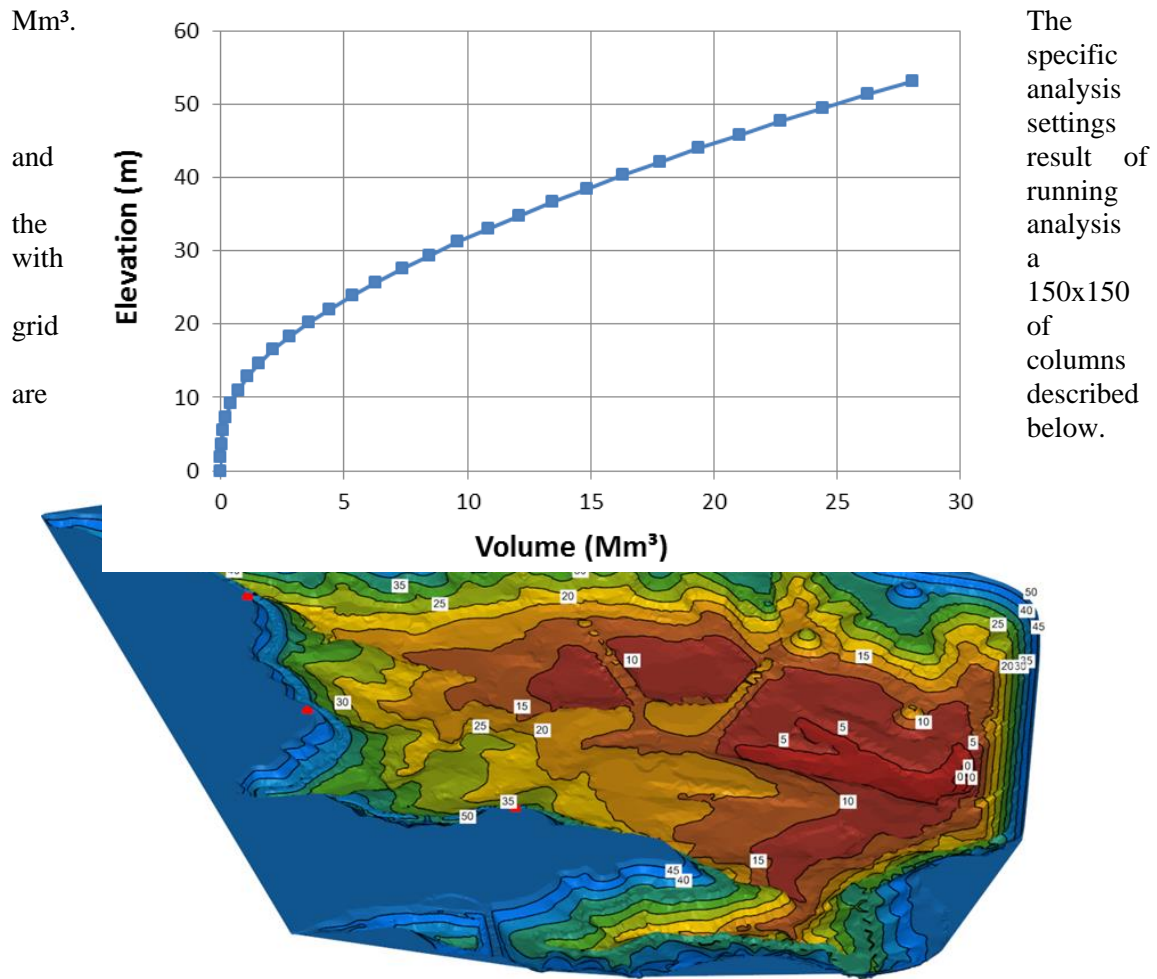


Figure 3: Case study TMF ground surface geometry

Figure 4: Filling curve for case study TMF

5.1 Stage Settings

The sequence of stages to be simulated is shown in Table 2. There are 6 years of tailings deposition with each year followed by a year of quiescent consolidation. The last stage is 188 years of quiescent consolidation which gives a total simulation time of 200 years. Note that consolidation also takes place during the deposition stages. This case study assumes that the water lost due to consolidation is drained from the tailings surface so that no ponding occurs. The water table is maintained at the top of the tailings throughout the analysis.

Table 2: Sequence of stage descriptions

Stage Number	Duration (days)	Action	Filling Rate (m ³ /day)
0	365	Deposition	12,000
1	365	Quiescent Consolidation	N/A
2	365	Deposition	12,000
3	365	Quiescent Consolidation	N/A
4	365	Deposition	12,000
5	365	Quiescent Consolidation	N/A
6	365	Deposition	12,000
7	365	Quiescent Consolidation	N/A
8	365	Deposition	10,000
9	365	Quiescent Consolidation	N/A
10	365	Deposition	9,000
11	365	Quiescent Consolidation	N/A
10	68,620	Quiescent Consolidation	N/A

5.2 Depositional Surface

The shape of the depositional surface is defined by three deposition points along the left-hand side of the tailings facility and a 0.5 degree downward slope representing the angle of repose for the tailings material. The locations of the deposition points along the edge of the embankment are shown as red dots in Figure 3. For each stage with a deposition action the depositional surface is constructed assuming equal tailings deposition volume and simultaneous deposition from the three deposition points.

5.3 Material Properties

The material properties for the tailings material are assumed to be generic properties for a tailings material. The compressibility constitutive relationship relating the void ratio, e , to effective stress, σ' , is represented by the Weibull function which has the following form:

$$e = A - B \exp(-E\sigma'^F) \quad [1]$$

where A , B , E , and F are data fitting parameters. The generic parameters for the compressibility function are listed in Table 3 and the graph of the function is shown in Figure 5.

Table 3: Compressibility relationship parameter values

Parameter	Value
A (kPa)	0.2
B	-3.0
E	0.2
F	0.8

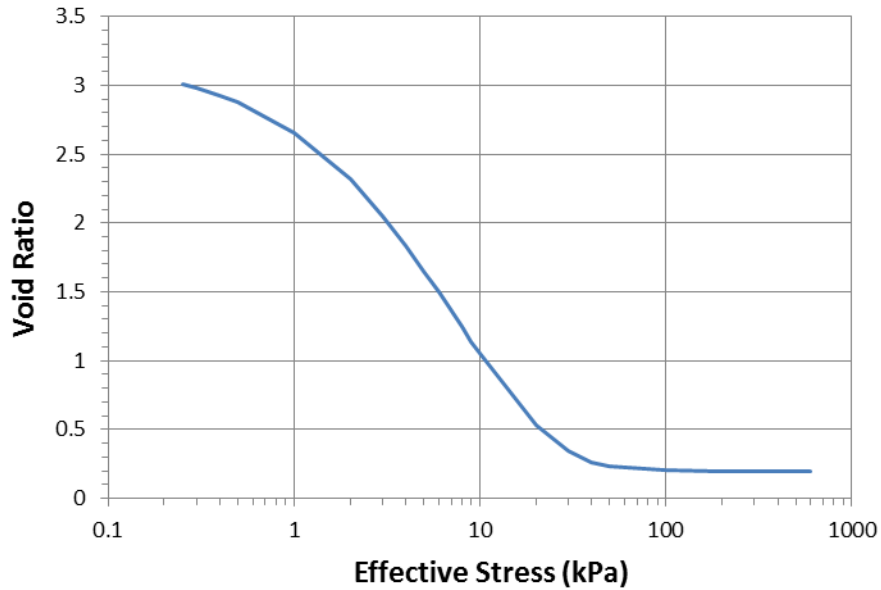


Figure 5: Graph of compressibility constitutive relationship

The relationship between hydraulic conductivity, k , and void ratio, e , is represented using a Power function which has the following form:

$$k = Ce^D \quad [2]$$

where C and D are data fitting parameters for hydraulic conductivity. The generic parameters for hydraulic conductivity are listed in Table 4 and the graph of the function is shown in Figure 6. The initial void ratio of the tailings as it is deposited is set to 3.0 and the specific gravity is set to 2.65.

Table 4: Hydraulic conductivity relationship parameter values

Parameter	Value
C (m/day)	0.001
D	3.0

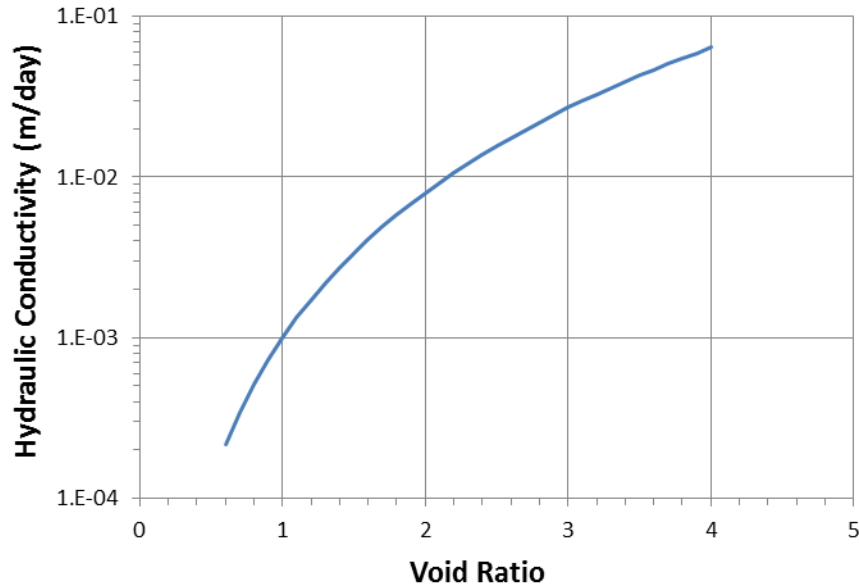


Figure 6: Graph of hydraulic conductivity relationship

5.4 Pseudo 3-D Analysis Results

A 40-core high-performance server was utilized to expedite the calculations for the pseudo 3-D analysis. The 150 x 150 grid of columns resulted in 10,864 unique 1-D model runs each of which had to be run out to 200 years. The analysis took just under 12 hours to complete.

The graph of volume of tailings over time is shown in Figure 7. The consolidation is essentially complete by the end of the 200 year simulation time. The total volume of tailings deposited was 24.455 Mm³ therefore the cumulative volume of water lost due to consolidation was about 2 Mm³ after 11 years and about 11 Mm³ after 200 years. Snapshots of the tailings facility at key points in time are shown in Figures 8-10. The effect of consolidation is evident near the edges of the tailings where the columns have less thickness leading to less settlement. In contrast, the columns near the middle of the tailings facility have a greater thickness leading to more settlement.

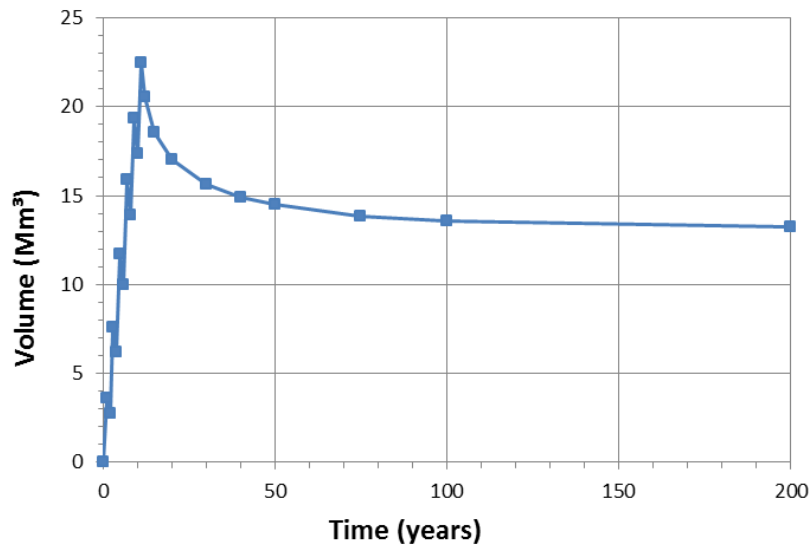


Figure 7: Graph of volume of tailings versus time

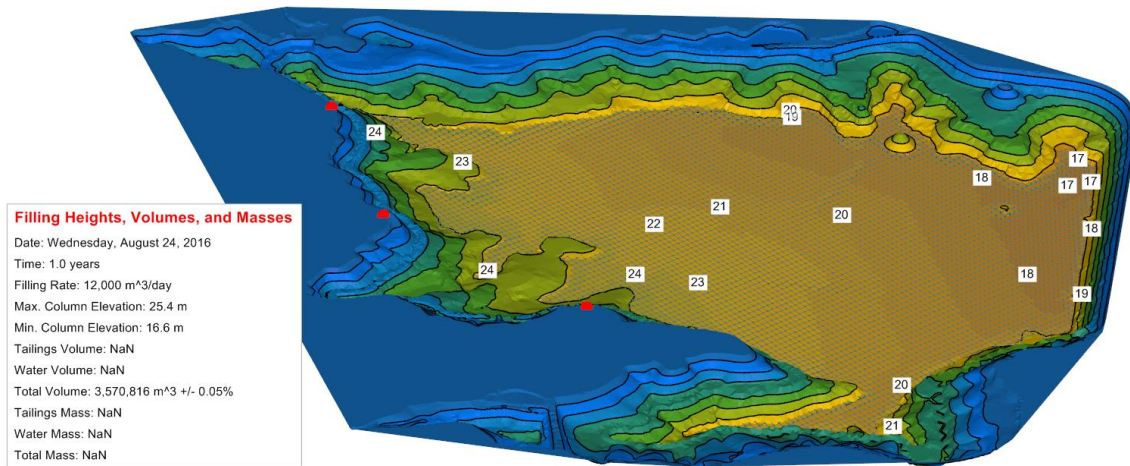


Figure 8: TMF at year 1

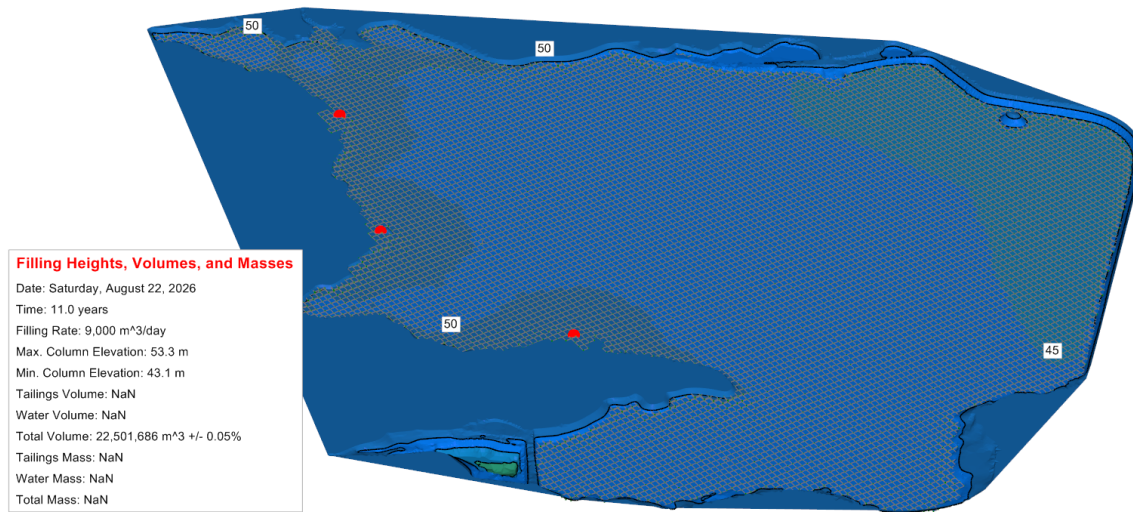


Figure 9: TMF at year 11

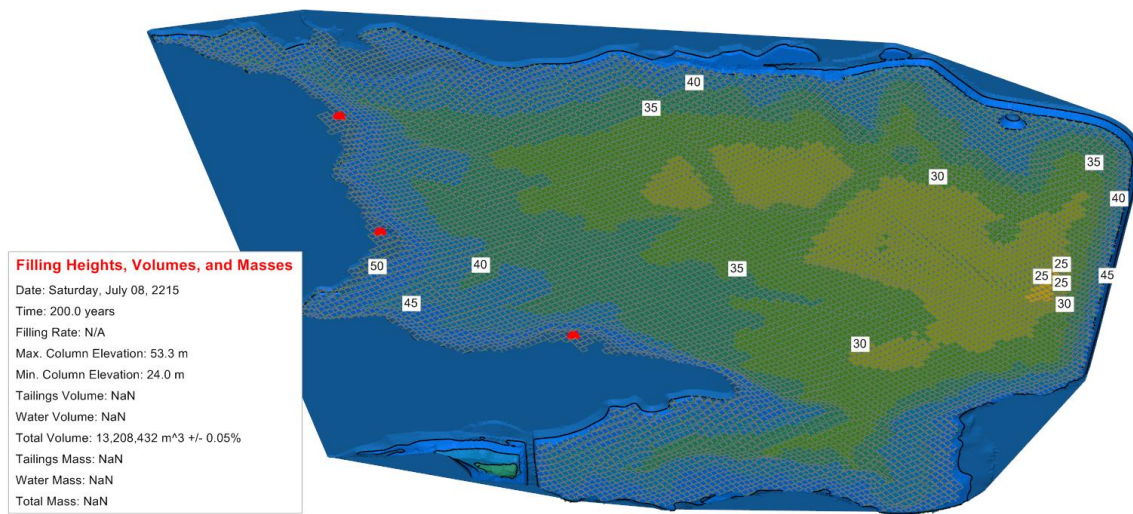


Figure 10: TMF at year 200

6 CONCLUSIONS

The methodology for performing a pseudo 3-D analysis of a TMF was described in detail and a case study was presented to illustrate the concepts and results of the analysis. The following advantages and disadvantages exist for the pseudo 3-D analysis methodology.

6.1 Advantages

- The analysis is stable and reliable because it is based on solving relatively simple 1-D numerical models
- The analysis is well suited for parallel computing
- Different depositional scenarios can be handled
- Climatic effects can be coupled with consolidation
- The analysis is ideally suited for facilities with a high horizontal to vertical ratio in their geometry
- The effect of bottom drainage can be easily represented in the numerical model

6.2 Disadvantages

- This methodology does not consider lateral seepage or lateral deformations
- The new method overall represents an improved methodology for the combination of depositional modeling and 1-D large-strain consolidation. The approach allows tailings planners increased rigor when calculating tailings volumes, decanted water volumes, and surface shapes as a function of time.

7 REFERENCES

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