

3D Deposition and Water Balance Modelling with Muk3D and GoldSim

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Abstract

GoldSim is a widely used simulation package that is frequently used in the modelling of water balances for mine sites and Tailings Storage Facilities (TSF). One limitation of GoldSim is that TSFs can only be represented as 2D structures using the available GoldSim modelling tools.

Currently, water balance models of the TSF pond assume a constant tailings storage shape, notably a conical shape or the stage-area-volume curve of the last survey. They can also be comprised of a set of stage-storage curves for the pond and tailings that are based on deterministic modelling. This is then applied to a long duration model. The result is that elevations and volumes predicted by the TSF model may not be accurate, and they may not always be relied on as a realistic prediction.

Muk3D is a 3D modelling tool that simulates the filling of TSF's based on the geometric representation of tailings behaviour. As tailings surfaces are formed within the model, the interaction with the pond and the underlying topography is simulated, leading to more realistic deposition surfaces that can better predict TSF behaviour than 2D models. Muk3D does not include a water balance component in its modelling toolkit, and so has always relied on the user entering relevant data about the behaviour of the pond when developing tailings plans.

This paper discusses how GoldSim and Muk3D have been integrated allowing for 3D tailings deposition to be incorporated into an existing water balance model. The difference in results between the 2D models for a TSF used in GoldSim and the same models run using a 3D deposition model are explored, and advantages and limitations of this approach are discussed.

Introduction

No mine has a neutral water balance over its life. Understanding which case a mine falls into at a given point in its life, and how it impacts the operation, is done with a Site Wide Water Balance (SWWB). This is a numerical model that is aimed at understanding the net inflows and outflows of water into the entire

mine site, and determining either the deficit (and make-up water required) or the surplus (and volume of water that must be released). Depending on the location, the costs for make-up water or water treatment can be significant. Mines that have a water deficit need to introduce fresh water to the operation (river, groundwater, ocean). Mines that have a water surplus need to either store it or release (and potentially treat) it.

The water balance needs to incorporate all water sources and sinks on the site, as well as capturing how water is moving between different elements of the site. These elements include the mine, the waste dumps, the process plant, the TSF, and any water storage structures.

For the TSF, the water balance serves several important functions. A principle goal is to predict the volume of water that will need to be stored in the TSF over its life. This volume affects the pond elevations, the beach formation, and the rate of rise of the perimeter dykes, and ultimately can influence the constructability and geotechnical stability of the dams.

Representing a TSF in a water balance can be challenging. The primary tools that are used for building water balances are not very good at simulating 3D structures, and instead the TSF's are represented as very simple 2D models. These 2D models are not good at capturing the behaviour of the TSF, and so some of the information generated from such models cannot always be taken to be a reliable prediction.

This paper will demonstrate why these 2D models are not an adequate representation and propose an alternative that incorporates 3D modelling of the TSF using Muk3D.

Tools for Developing Water Balances

Regardless of the tool used to create the water balance model, the aims are the same. On a macro scale, the water inflows and outflows from the mine site are considered. Global inflows comprise two main components – water that enters the system that we have no control over (e.g. rainfall, snowmelt, dewatering) and water that can be controlled (make-up water pumped from the river, ground water, ocean, or other source). Global outflows are losses that are uncontrolled (seepage, evaporation) and those that can be controlled (release, treat, and release).

Two common tools used to develop water balances are Microsoft Excel and GoldSim. Excel is a widely used tool given its accessibility and ubiquitous use throughout the engineering world. The other tool that is commonly used is GoldSim software (version 12), developed by the GoldSim Technology Group LLC. GoldSim is a probabilistic simulation and modelling software package that has been extensively used for the development of graphically-oriented models with developed logic for networks, including pit lake water balances.

The model operates at a daily time step and is used to predict the TSF pond water level and volume. The volumes of these ponds are driven by rainfall, evaporation, and TSF deposition. A model is created by connecting basic elements that perform logical or mathematical functions and ultimately allow for the simulation of a complex process. Once a model has been built, probability distributions can be assigned to input data, allowing for stochastic modelling to be undertaken. Instead of providing a deterministic result, stochastic modelling provides a range of output values that can then be used to understand probabilistic outcomes, including the most likely/worst outcomes.

Simulating TSFs in GoldSim

GoldSim models are constructed by connecting processing elements that perform basic calculations, an example of which is shown in Figure 1. TSFs are generally represented as a reservoir, which is a modelling element that keeps track of inflows and outflows of solids and water. Lookup tables are then used to take the volumes in the reservoir (tailings and water) and predict elevations (pond and beach), and pond surface areas.

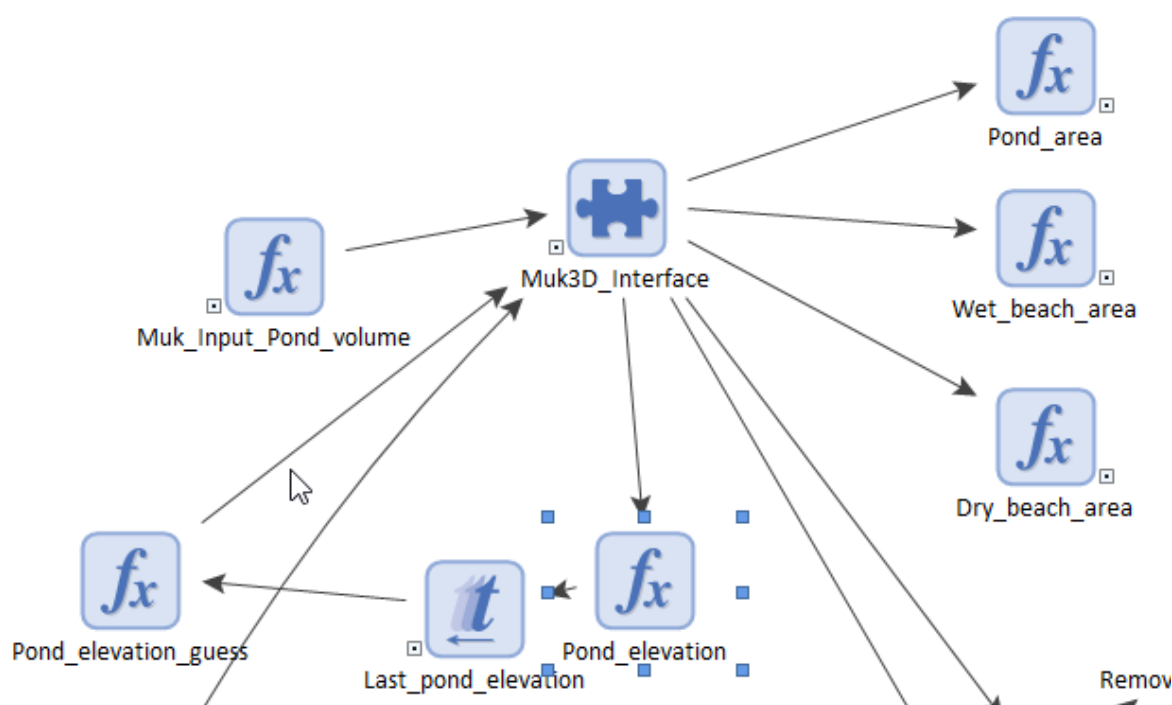


Figure 1: GoldSim elements connect to create a model

The main challenge with simulating a TSF accurately in GoldSim is that it is virtually impossible to model the 3D shape of a 3D phenomenon in 2D, and model how this evolves over time, for all but the simplest configurations. (The 2D model inherent assumption in the absence of 3D information.) As

tailings are poured into a TSF, the geometry of the TSF changes as the beaches are formed. The way the beaches build up is influenced by the pond elevations. The pond elevation depends on the beach formation and how much tailings are deposited below vs. above water, among other things. Thus, trying to model this over time and in 2-dimensions with storage curves and lookup tables is not a simple task.

The TSF geometry affects the pond area, which in turn affects the pond volume through augmentation in areal evaporation, rainfall, and runoff. If the evolution of the TSF geometry cannot be modelled accurately, then outputs from the water balance model that depend on pond and beach elevations, pond depths, and pond areas must be validated against 3-dimensional modelling to assess their accuracy.

There have been some approaches that people have tried to improve the simulation of a TSF using the elements that are available in GoldSim. Hoekstra (2017) discusses three methods that simulate the TSF as an inverted cone (one considers the pond to be a cone, while one of the others is a wedged version of the cone), and the use of 2D lookup tables that attempt to add a time component into the lookup process.

The approaches discussed in this paper are for the modelling of “conventional” TSFs that have beached tailings with water going to a pond. This could cover cross-valley, ring dykes, or in-pit disposal systems. This approach would not be suitable in its current form for paste and thickened tailings deposits (e.g., down-valley discharge or central thickened discharge).

It is also important to note that these simplified modelling approaches neglect to account for the 3D shape of the tailings beach. The GoldSim-only model cannot properly account for the change in beach slope at the pond elevation, and instead assumes that the beach is uniform above and below water. This is seen as a significant limitation to modelling TSFs in a realistic way. This is the limitation the integration of a 3D deposition model is aimed at fixing.

Inverted Cone Approach

This method of modelling the TSF involves treating it as an inverted cone that is gradually filled up. Figure 2 shows schematics of the two conical models. A uniform beach slope above and below water is assumed. By using basic geometric calculations, it is possible to predict depths, areas, and pond elevations, based on the volume of the tailings in the beach, and the volume of water in the pond. The inverted cone would be applied to the situation where the pond is centralized in the TSF, while the wedged inverted cone is more applicable to cases where the dam is against a dam. This is combined with the fill-elevation curves for the empty TSF, the assumed beach slope, and area-volume lookup tables.

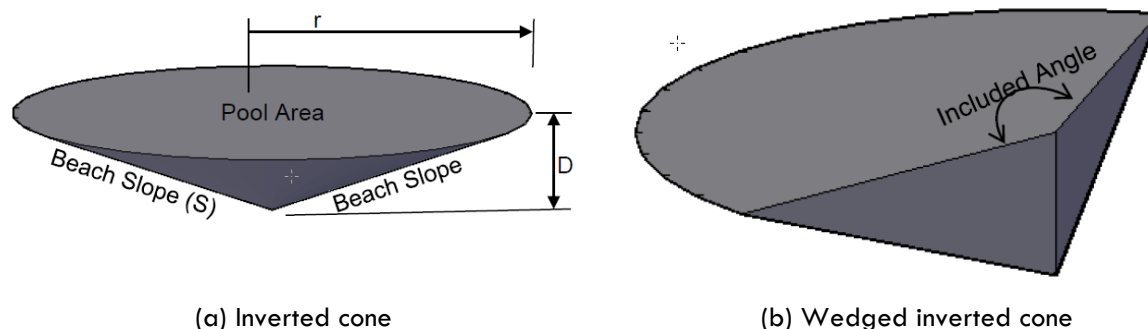


Figure 2: Schematics showing the cone models

The immediate problem with this model is that it relies on a uniform beach slope, which is generally not the case in operating TSFs. Thus, elevations, depths, and areas from this approach will not be accurate. The other problem is the assumption that the pond is conical/circular. Again, most TSFs do not have a pond configuration that mimics this. For example, in square paddocks, the pond might be better represented as an inverted pyramid.

Storage Elevation Curves (Tabular Method)

Storage curves are developed for different phases of the TSF life. Hoekstra (2017) and Donnelly (2017) have shown how interpolation between these curves can be done, and believe that it offers a more robust approach to modelling the TSF geometry over time. The idea behind this approach is that the storage elevation curves for the pond evolve over time to reflect the filling of the TSF. During calculations, intermediate storage elevation curves for the pond are interpolated based on the deposited volume of tailings, and these are used for predicting tailings and pond elevations, and pond areas.

Since the method uses storage elevation curves generated from 3D modelling, it has the advantage that the deposition could be done using realistic beach slopes above and below water. This would be fine for doing purely deterministic analysis (e.g., the pond has specific volumes over time, perhaps dictated by operational requirements); however once the inputs that would be used to generate the storage curves (different deposition configuration, different pond volumes, different beach slopes) are added, the pre-generated storage elevation curves become invalidated and the model may no longer predict elevations accurately.

Other Options

Coding a 3D TSF deposition module using the script element in GoldSim may be possible, but it is difficult and requires knowledge and experience in TSF deposition model development and coding in GoldSim. However, using the basic GoldSim calculation elements, there are few other options for

creating accurate 3D models for the TSF over time. The models discussed above might give acceptable answers for simple TSF configurations, or might be adequate in water balance models where the 3D behaviour of the TSF does not have a significant impact on the system (e.g., for site-wide water balances where the TSF makes up a small component of the overall system).

GoldSim does provide an element that allows interaction with Dynamic Link Libraries (DLLs). This is code that is compiled and allows for execution of numerical calculations outside of GoldSim. The use of this is explored in the following sections.

Modelling TSF with Muk3D

Muk3D is a 3D CAD tool that is specialized for the design and modelling of TSFs. It is a geometric model that allows tailings beaches to be created using assumed beach slope profiles.

One of the limitations of Muk3D is that it does not have a water balance model built into it, and so as a designer is running through a deposition plan they need to manually extract relevant data from the mass and water balance model (target pond volumes, deposited volume of tailings) to incorporate into the 3D model. Results of the deposition modelling (beach elevations, pond elevations and areas, beach areas, and storage elevation curves for the resulting basin, for example) are then entered back into the water balance model to improve the accuracy of subsequent calculations.

Comparison of GoldSim Pond Models with Muk3D Predictions

To compare some of the GoldSim based TSF models with Muk3D, a model from the GoldSim library was used (GoldSim, 2017b). This is a model prepared for a GoldSim web-based seminar that compares the conical, conical with wedge, and tabular approaches. The comparison with Muk3D was done by exporting tailings and pond volumes to a CSV and using this to drive an automated Muk3D model to deposit the target tailings volume with the target pond volume.

Circular Ring Dyke

The first scenario being considered is one that most closely resembles the conical shaped TSF pond models: a circular ring dyke with a centrally located pond. In this hypothetical example, the ring dyke is located on slightly sloping ground, so for at least some of its early life there will not be full perimeter discharge, which would simulate the wedged cone scenario. Once tailings have been built up enough, it becomes the inverted cone model. Figure 3 shows the basic configuration for the facility.

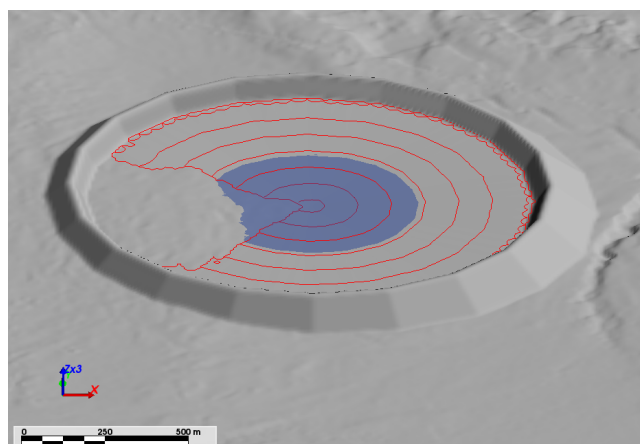


Figure 3: Basic configuration of the circular ring dyke model

For this model, the same production volume of tailings and volume of pond water were applied to the GoldSim conical models and the Muk3D model. The GoldSim models were simulated daily, while the Muk3D model was run for the end of every month, for a 4-year period (48 runs). This was done out of practicality, since each Muk3D model takes between 20 seconds and 120 seconds to run.

In the Muk3D model, the tailings are assumed to have a uniform density and a uniform beach slope above and below water (1%). Muk3D was run to goal seek the beach elevation and pond elevation for the incremental volume of tailings and the end of month volume of water, respectively.

The predicted pond elevations and areas for the 3 models are shown in Figure 4.

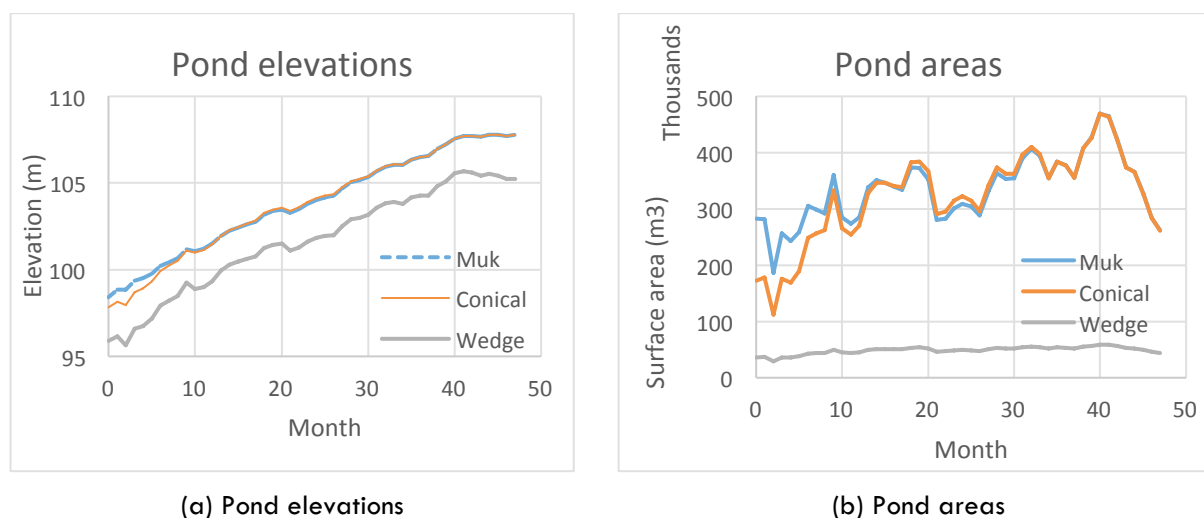


Figure 4: Results for conical modelling runs

We can see that in this scenario, the conical model closely matches the Muk3D pond elevation predictions. Once the model gets past Month 35, the Muk3D and conical elevation predictions are almost identical (the average difference between month 35 and month 48 is 1.6 mm). At month 35 the deposition

starts to approximate the cone being used, as illustrated in Figure 5. In earlier time steps, the basin geometry is not conical due to outcrops of original ground, and so the conical approximation is not a great model. The conical wedge model did a poor job of predicting pond elevation in this case. While it tracked the relative changes well, it was consistently off by around 2 m.

Comparison of pond areas shows similar agreement between the Muk3D and conical models, while the wedge model failed to give a reasonable approximation, as shown in Figure 4(b).

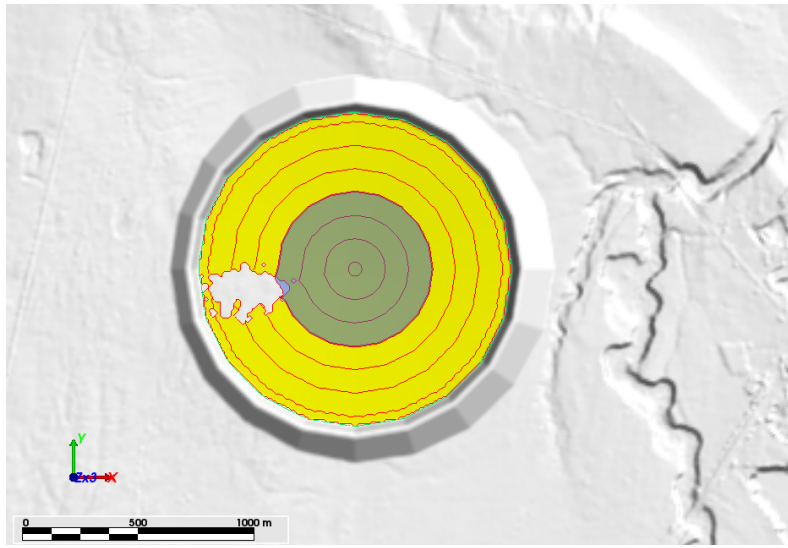


Figure 5: TSFF at month 35

Square Ring Dyke

To test the conical TSF models for a different dam geometry, a square ring dyke was created and filled with tailings and water, using the same assumptions for the conical model discussed above. The configuration is shown in Figure 6.

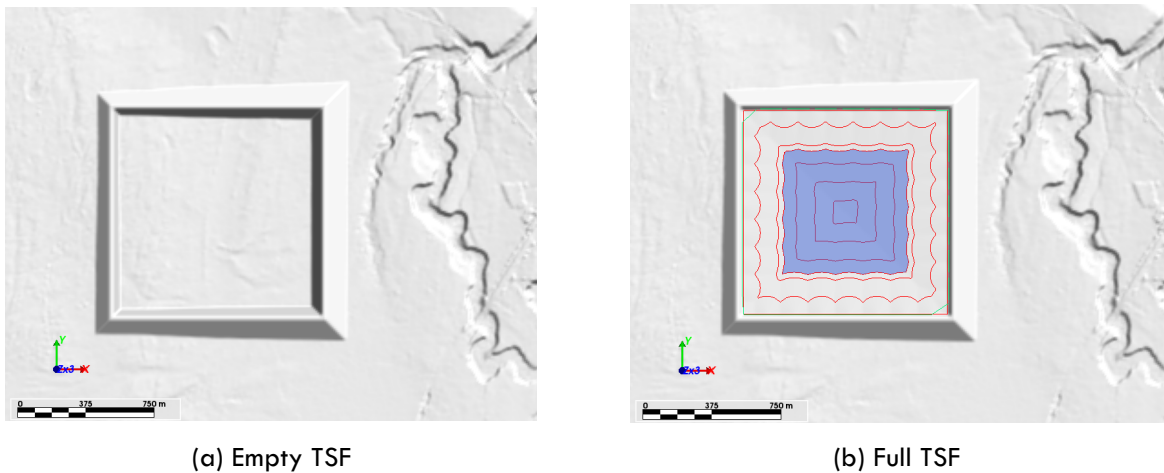


Figure 6: Square ring dyke model empty and with some tailings deposited

A comparison with the tabular approach was also undertaken for this configuration. Storage-elevation-area curve data was generated for five points in the life of the structure (no tailings, and tailings at four different elevations).

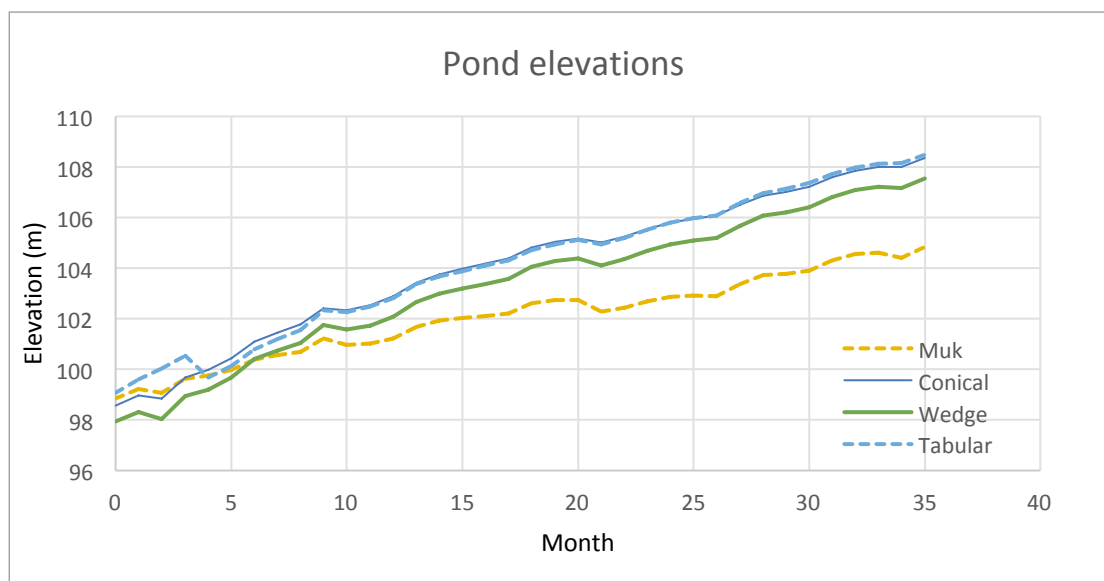


Figure 7: Pond elevation predictions for a square ring dyke

The results presented in Figure 7 show that the conical model does not accurately track the elevations, compared to the 3D deposition modelling. The tabular method results were very close to those of the conical model.

If the conical model was adapted to an inverted pyramid, then it is possible that it would provide a better prediction of pond elevations, especially once a full inverted pyramid shape is formed by the beaches (i.e. the tailings deposit is high enough that all original ground has been inundated). For an equivalent dimensioned pyramid vs. a cone (where diameter of the cone is equal to the side length of a pyramid), the cone has 78% of the volume of the pyramid. The smaller volume means that higher elevations will be reported for the conical model of a given volume of tailings and water.

Issues with Simplified Models of TSFs and Ponds

All the examples that have been considered here use a uniform beach slope, regardless of whether the beach is above or below water. In practice, it is probable that the beaches will have different slopes above and below water. For operating TSFs, where beach profiles can be measured, it is likely that the beach slopes are non-linear. This adds a further level of complication to modelling. At a high level, these simplified models of ponds may be adequate for Site Wide Water Balances (where the overall flows of water are considered more important than predictions of elevations from the TSF); however, for the TSF planning work they are inadequate.

Models that are more focused on the behaviour of the TSF, where designers are trying to understand the behaviour of the structure in the short and long term, require a more detailed model. This is where the ability to model a pond in a more rigorous way using Muk3D provides an advantage.

While some of the shortcomings of the conical TSF models could be overcome using the method of interpolating storage Elevation curves, it must be remembered that these input curves are only applicable for a single operating scenario. If there is more or less water, more or less tailings, different beach slopes, different densities, etc., the storage elevation curves for a facility will change. The beaches will form a different shape, and so these inputs would change. From the point of running these simulations in GoldSim it negates the ability of GoldSim to run a range of scenarios, and have the model react appropriately to each of these runs.

Integration of Muk3D deposition models within GoldSim

In the examples shown above, the Muk3D modelling was done by exporting the tailings and pond volumes to a CSV and running the deposition models using a macro written to read the inputs from the CSV. GoldSim provides no direct program integration outside of Microsoft Excel, and some database formats, as a mechanism for reading and writing data. It does however have an element that allows linking to a Dynamic Link Library (DLL).

Using example DLL code published by GoldSim (2017b) that allowed for Python code to be executed (Python is also used by Muk3D for scripting), a custom DLL was developed that allowed GoldSim to send data to Muk3D, wait while Muk3D does some processing, and then receive results back. Currently Muk3D can accept any number of variables from GoldSim if they are either Scalar or Vector data types. Muk3D can return scalars and 1D lookup tables, currently.

When Muk3D receives information from GoldSim, it needs to know what to do with it. A script is written in Muk3D that performs a set of actions and returns the required data to GoldSim.

A Simple Example

A simple implementation of Muk3D/GoldSim linkage was done using the following configuration:

- Square ring dyke, as illustrated in Figure 7.
- The pond is driven by a target volume. In practice it would come from a water balance volume, but in this example, it comes from a Random Walk element, the same as in the GoldSim models run for comparing methods.
- Tailings volume comes from the mass balance model. In this example the tailings are being deposited at 8,000 m³ of deposited tailings per day.
- The Muk3D model is run using a 28-day time step.

The GoldSim model used was after Hoekstra (2017), which was modified to include the Muk3D deposition as a module within GoldSim. This model is not a water balance but an illustrative example that has deterministic pond water and tailings volumes.

Setup within Muk3D

To set up a GoldSim link in Muk3D, the interface (GoldSim inputs and outputs) need to be defined. Python code was written to tell Muk3D what to do when data from GoldSim is received. In this case, it tells Muk3D to deposit a volume of tailings (GoldSim input) from some pre-specified locations, with a target pond volume. Muk3D will solve for beach elevation and pond elevation. Data returned from the model is:

- Pond elevation;
- Beach elevation (maximum beach elevation);
- Pond depth;
- Storage elevation curve for the new pond (above the tailings surface).

Setup in GoldSim

Within GoldSim, the link to Muk3D is done by using a DLL element that links to the Muk3D DLL file, and defines a set of inputs and outputs. The inputs are the values that Muk3D needs to do “something” with. The outputs get fed back into the GoldSim model. The storage curve for the new basin geometry that was generated at the end of each Muk3D deposition run was used as the input to a 1D Lookup Table element in GoldSim, and the Muk3D pond elevations were checked by looking up the pond volume.

Results

The model was run for a 6-year period, with Muk3D deposition runs every 28 days. A summary of results for beach and pond elevations is shown in the graphs in Figure 8.

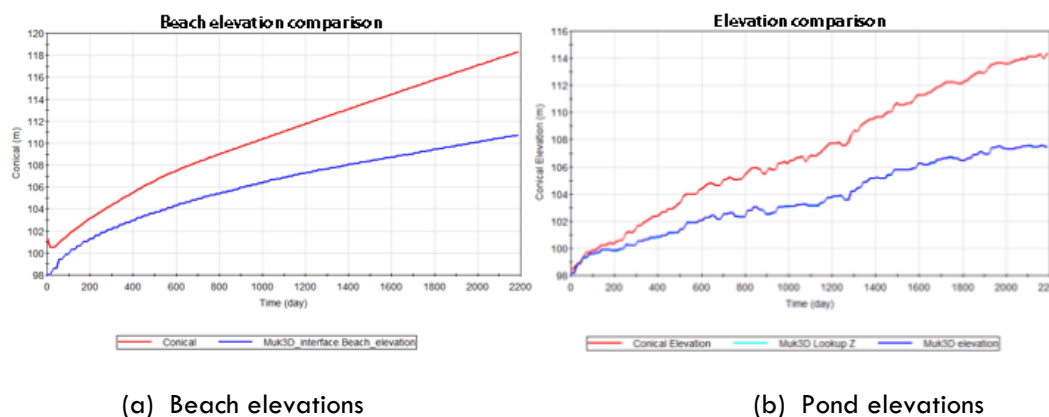


Figure 8: Elevation predictions for conical and Muk3D model from GoldSim

The results are consistent with the examples shown in previous sections, which is to be expected. The difference is that these values were generated by GoldSim directly interacting with Muk3D. The pond elevations calculated from the volume-elevation curve returned from each Muk3D run are barely discernible on the graphs as they are coincident with the Muk3D elevations.

Limitations

Running a 3D deposition model does take a lot longer to get a result than using the simplified approaches covered in this paper, and so it is not feasible to do a daily simulation, over a long time period, incorporating the 3D deposition model. Muk3D uses a goal seeking approach to determine what a tailings surface looks like when it must deposit a given volume of tailings and hold a pond with a given volume of water.

To consider the shorter-term behaviour of the TSF would require additional logic in how tailings are deposited in the TSF. This example is pouring tailings around the entire perimeter, but when looking at very short time frames, that is not how the TSF is operated.

Future Work

Now that a reliable interface between Muk3D and GoldSim has been developed, the goal is to further test this linkage on more complicated projects. The examples used in this paper are trivial and do not reflect the range of operating philosophies, distribution systems, pond management strategies, or tailings profiles that would be encountered in practice.

The big opportunity that this modelling approach offers is the ability to run stochastic models, varying key parameters in the tailings deposition/water balance models, and starting to understand the impact that uncertainty has on the predicted behaviour of the TSF. Instead of running a single option, the opportunity to run a model with varying inputs (water volumes, tailings volumes, beach slopes, tailings densities, etc.) is possible. This provides the opportunity to better understand how a TSF reacts to different scenarios, or modelling inputs.

Conclusions

While GoldSim is a great tool for modelling TSF water balances, it lacks the ability to represent the evolution of 3D structures accurately. The application for the model and the type of structures being modelled may affect the results significantly.

Muk3D is a good tool for simulating TSFs, but it lacks the water balance component. By integrating the two pieces of software, the limitations that are imposed by each of them can be overcome and thus allows for more representative modelling of a TSF.

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