Hydrogeological Inputs to Stability Analysis of Tailings Storage Facilities

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Abstract

Traditional stability analyses of tailings storage facilities (TSFs) are often undertaken utilising two-dimensional methods. Sections of the facility are targeted using Cone Penetration Testing (CPTu) to obtain data related to the phreatic surface and pore pressure distribution in the TSF. This data is analysed numerically in two-dimensional space, often representing the facility in isolation from the underlying aquifer system. With the emergence of the GISTM a more integrated approach to seepage modelling in TSFs is now required. The integration of the interaction between a TSF and the underlying groundwater in three-dimensional space is crucial to understanding factors influencing its internal pore pressure distribution. Hydrogeological flow modelling provides a tool to simulate external influences on TSFs, thus integrating seepage from various sources into- and out of a facility, and potentially influencing its stability. This paper presents examples where numerical groundwater flow modelling in three-dimensional space has provided valuable inputs to TSF stability analyses. Three facilities located in West- and South Africa are presented where numerical groundwater flow modelling was applied, utilising CPTu data as calibration points. Each facility was geometrically defined using as-built construction information provided, along with hydrogeological information of each location. Additionally, the hydraulic parameters of the tailings materials and underlying aquifers were calculated based on standard testing methodologies and incorporated into each simulation. Each model was able to simulate the phreatic surface and seepage rates within each respective TSF, as confirmed by CPTu data and measured underdrainage volumes. Further verification was performed by calibration against groundwater level monitoring data. The constructed models clarified internal and external influences on the pore pressure distributions of the simulated TSFs, which aided greatly in targeting potential areas where elevated pore pressures may pose a risk of current- and future instability. Stability analyses could be performed on the identified areas which aided in the development of mitigation measures to lower the risk of tailings instability. Based on the findings of the work performed, it can be concluded that three-dimensional hydrogeological flow modelling, including TSF integration, provided additional insight into the characterisation and quantification of pore pressure distribution in tailings facilities. Detailed phreatic surface calculation can be utilised to identify areas of potential liquefaction risk where two-dimensional stability analysis can be applied to develop the necessary mitigation measures. Additionally, a more complete conceptualisation of external influences affecting the pore pressure distribution in TSFs can be formulated through numerical groundwater flow modelling.

Keywords: Hydrogeology, numerical modelling, tailings, TSF stability, pore pressures

Introduction

With the advent of the Global Industry Standard on Tailings Management (GISTM) a more holistic approach to tailings management is required (International Council on Mining and Metals (ICMM), United Nations Environment Programme (UNEP) and Principles for Responsible Investment (PRI) 2020). Principle 2 of the standard requires the development and maintenance of an interdisciplinary knowledge base to support the safe management of a TSF throughout its lifecycle. Under Principle 2, Requirement 2.2 expects a detailed site characterisation of the TSF, which includes a hydrogeological investigation that must be updated regularly. Furthermore, Requirement 2.3 under Principle 2 expects a breach analysis of the TSF that considers credible failure modes, site conditions, and the properties of the slurry. This study presents calibrated numerical simulations that illustrate the interdependence of these requirements as TSFs can often be hydraulically linked to groundwater. This hydraulic linkage could potentially result in outflow of contaminated TSF pore water to the underlying aquifer, or inflow of groundwater into the TSF through liner systems, potentially causing pore pressure build-up within the facility, leading to instability. Hydrogeological flow modelling was utilised to identify potential hydraulic interdependence between TSFs and underlying aquifers, with calculated phreatic surfaces used in stability analyses for each facility.

Methods

As part of the geotechnical investigation at each of the three facilities considered in this paper, surface electrical resistivity tomography (ERT) lines were completed along the flanks of the TSF. In addition to the ERT survey, seismic refractive and multi-channel analysis of surface waves (MASW) surveys were also completed. This data was used to delineate various lithologies and focus areas for drilling and test-pitting. Once identified, geotechnical rotary core boreholes, Overburden Drilling EXcentric (ODEX)- and Down-The-Hole (DTH) rotary air percussion boreholes were completed around each facility (in various combinations) to characterise the local geology surrounding the TSF. Upon completion and construction of the percussion boreholes, pumping tests were performed within the regolith- and weathered aquifers encountered during drilling to define the hydraulic parameters of these hydrostratigraphic units. To further refine the hydrogeological data collection at each site, especially with regards to structural discontinuities, dual-packer testing was performed in the completed core boreholes, within the fractured aquifers on site.

Once the geological- and hydrogeological conditions around each TSF were characterised, further investigation was performed regarding the internal structure of the facility itself. As-built drawings and historical designs were reviewed to determine the position and geometry of the starter wall, underdrainage system, liner system (if present), outer wall, slimes, and penstocks (if present). Liquefiable zones within the tailings pile were identified and delineated, along with the phreatic surface in the facility using Cone Penetration Testing (CPTu), providing insight into the hydraulic properties of the materials present.

Utilising the data collected, a numerical flow model was constructed for each site which included the geometric features of the TSF and incorporated the hydraulic properties of each. Thus, the TSF is seen as an anthropogenic aquifer system within the hydrogeological model, allowing for the calculation of the pore pressure distribution within the facility. Furthermore, the direct recharge and groundwater flow into the TSF can be quantified, along with outflow rates from the facility. Inflow to the facility is represented by fluid-flux (Neumann) boundary conditions, while the underdrainage system of the facility can be represented by hydraulic head (Dirichlet) boundary conditions. Each model was constructed and calibrated using FEFLOW™ software (developed by the Danish Hydrological Institute) and used to simulate the aquifer-TSF systems as hydraulic continuums. The models were calibrated against measured groundwater levels in completed boreholes and monitoring wells, as well as the phreatic surface within each TSF, as identified from CPTu data.

Results and Discussion

Based on the studies performed and data collected, integration of natural and anthropogenic aquifer systems into a single numerical flow model yielded realistic results (fig. 1). Geometric data integration into the flexible meshing system provided valuable insight into the external water sources that could be affecting each facility. In the example provided in fig. 1, a nearby flooded open pit mine was shown to be hydraulically connected to the facility, and seeping through the clay liner on the hillside where deposition takes place, via intersecting fault systems. The integration of the regolith layer underlying the TSF is crucial in identifying hydraulic pressure zones under the base of the facility, which could result in groundwater influx into the TSF if any liner damage may be present. Furthermore, a raise in the depositional elevation of the facility could be incorporated into the model to evaluate its effect on the phyllitic waste rock buttress that was constructed around the outer embankment of the TSF.

Findings related to pore pressure distribution calibration showed that a 1% to 6% error range in simulated hydraulic head elevation is likely to be typical for this type of model, based on the facilities considered in this study (fig. 2). The calibration graph (fig. 2) and associated statistics for a model constructed for a South African gold TSF showed an average Root Mean Squared Deviation Percentage (RMSD%) of 5.9%. The calibration was based on the hydraulic heads

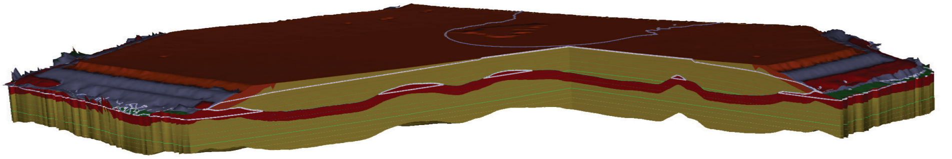

Figure 1 *Section of a Ghanaian TSF integrated into a numerical groundwater model*

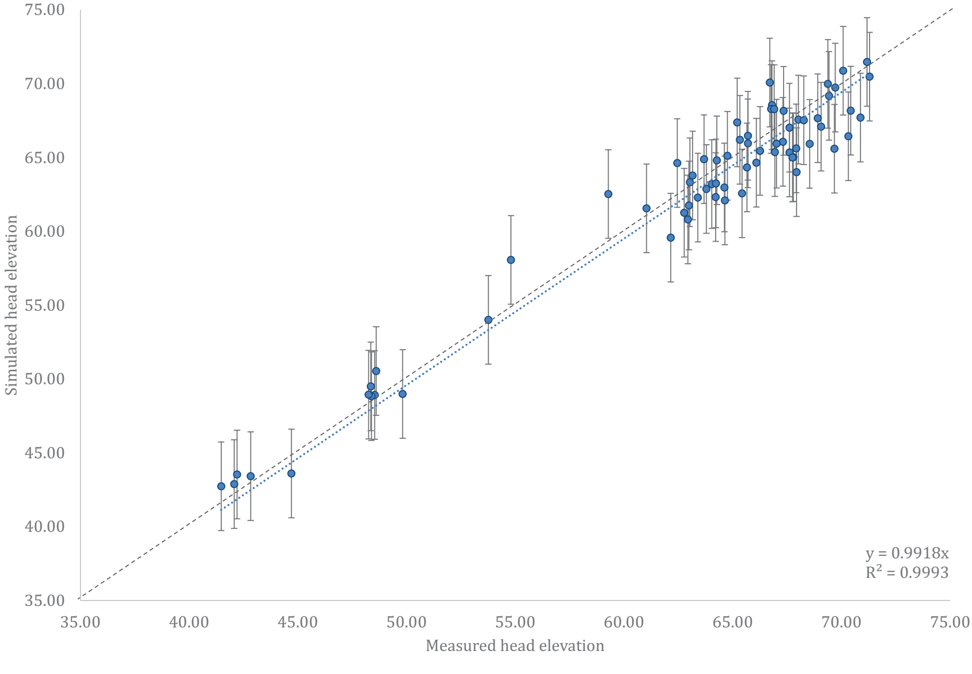

Figure 2 *Calibration graph of measured hydraulic head elevations compared to simulated hydraulic head elevations for a South African gold tailings storage facility*

measured in newly drilled- and constructed monitoring wells surrounding the facility, as well as the phreatic levels within the TSF obtained from the CPTu data collected during the site characterisation.

Once calibrated, the flow budget for each model was exported to determine flow rates through each facility, and also compared to measured underdrainage system flows, where available. Potential groundwater inflow and TSF seepage could therefore be quantified, along with the identification and quantification of components contributing to the overall TSF water balance, in agreement with the work of Karimi et al. (2023). Evaluation of the flow budgets showed that the surface area, depth, and shape of the supernatant ponds on TSFs are major drivers for the hydraulic behaviour of the facility. Although this may appear self-evident, the evaluation of the phreatic surface and flow within the TSF should be considered in conjunction with the influence of potential groundwater inflow highlighted in the flow budget. Anomalous flow rates and -directions, as well as excess pore pressures are often a combination of supernatant pond seepage and groundwater influx (fig. 3).

Potential high-risk inflow areas were consistently identified in each model and the effects on stability were subsequently calculated (fig. 4). This was performed utilising the calculated phreatic surface within the TSF, in conjunction with the engineering parameters and distribution of the materials present, in two-dimensional space. Liquefiable zones within each facility could be identified, accounting for external influences on the pore pressure distribution in each TSF, including potential future hydraulic behaviour of the material. This greatly improved the performance of routine stability assessments, after inclusion of additional data and seepage simulations. An added benefit to these simulations is the possibility to calculate the stability of future raises to each TSF (fig. 4).

Based on the data collected, seepage simulations and stability assessments performed, additional monitoring positions could be identified for each TSF. These positions were related to the identification

Figure 3 *Elevated hydraulic pressure zones due to groundwater influx at the base of a South African gold tailings storage facility*

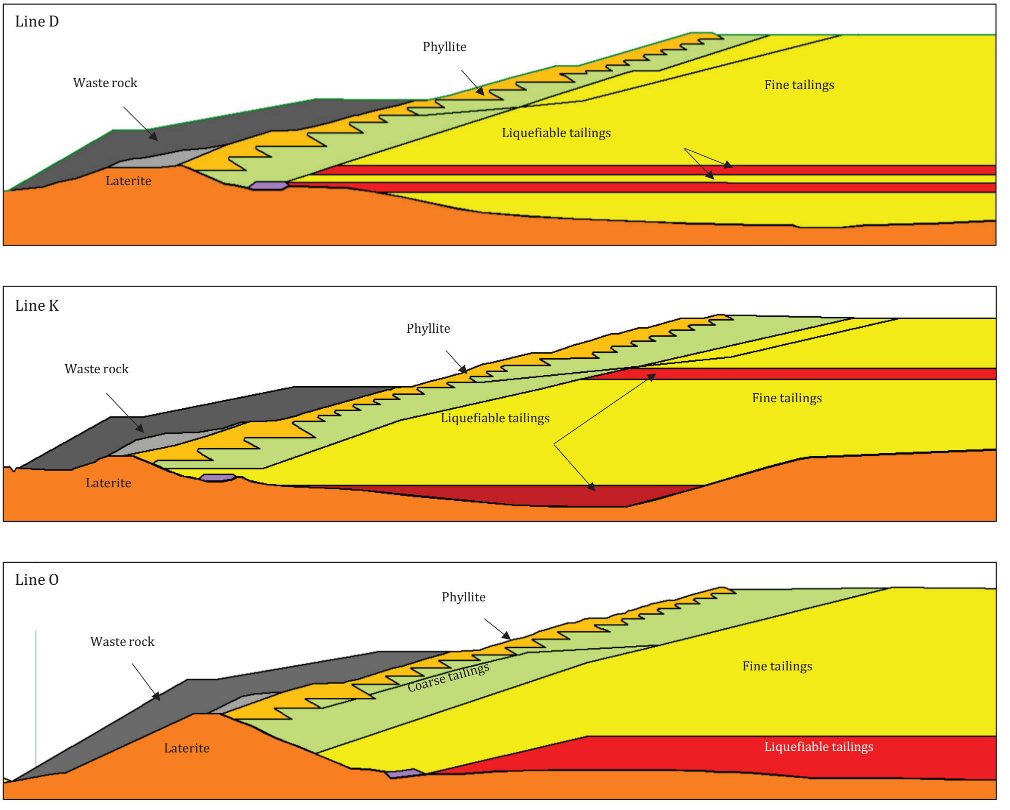

***Figure 4** Zones of liquefiable tailings identified in a Ghanaian tailings storage facility*

of zones of instability, liquefiable tailings zones, damaged underdrainage systems, and damaged liner systems, similar to the work of Garrick et al. (2014). Future piezometer- and monitoring well positions were mapped accordingly for each facility, monitoring the phreatic surfaces in the TSF, regolith aquifer and weathered aquifer at each site. The data collected at these positions will be used to further refine the understanding of the aquifer-TSF hydraulic continuum in future.

Conclusions

Studies performed at the tailings storage facilities considered in this paper illustrate a common theme, which is the importance of incorporating the hydrogeological influences on a TSF in numerical flow modelling. This finding is similar to those of Levenick et al. (2009). The numerical integration of natural and anthropogenic aquifer systems at each site consistently yielded realistic results in comparison to groundwater monitoring well- and CPTu data. The pore pressure distribution calibration for each model shows a typical 1% to 6% error range in simulated hydraulic head elevation. The flow budget for each model illustrated potential groundwater inflow and TSF seepage, which could be quantified. Anomalous flow rates and -directions, as well as excess pore pressures were found to be a combination of supernatant pond seepage and groundwater influx, with potential high-risk inflow areas consistently identified. Liquefiable zones in each TSF were successfully identified and additional monitoring positions were recommended for each TSF. Based on the findings presented, it is concluded that numerical groundwater flow models can be utilised to assess the holistic hydraulic behaviour of TSF-aquifer continuums, and successfully account for groundwater related influences on TSF stability.

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