Development of a 3D ground model to design the stabilisation of a dam founded on weak liquefiable ground

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ABSTRACT. A three-dimensional (3D) ground model was developed to design the stabilisation of a dam founded on both weak and liquefiable units up to about 18 m below ground surface. The ground model covers a linear extent of approximately 800 m and was developed from five separate site investigations completed over a four-year period and digitisation/georeferencing of historic drawings/plans. Combined, the investigation comprised 206 cone penetration tests (CPTs), 37 boreholes and 36 test pits, including several vane shear tests, ball penetrometer tests and sampling. CPT data was processed to identify different material behaviours, generally based on the following features: corrected tip resistance; sleeve friction resistance; pore water pressure ratio; state parameter; and the soil behaviour type index. Each CPT interpretation was compared with information from the nearest borehole using a purpose-built python code. This information was reviewed manually in an iterative process to delineate the various geotechnical unit based on CPT response and the physical logs. This process identified a continuous weak organic layer across the site which had not been previously picked-up by the Engineer of Record (EoR). The works identified nine separate geotechnical units, with one of these subdividable based on its CPT response/grain size. The 3D ground model was built in Seequent Leapfrog Geo using the following information: unit levels specified from each CPT, digitised historic drawings/plans and a topographic survey. This paper describes the process of development and presents the full 3D ground model used as critical input to the stabilisation design of the dam.

Keywords: Ground Model; CPT; Soft clay; Tailings Dam; Leapfrog

1 Introduction

Review of a dam identified that historic tailings deposits (from mid 1950s) and natural materials found in the foundation are weak and potentially liquefiable, with a depth up to about 18 m below the ground surface at the dam toe. The dam embankment was designed as a water retaining structure (i.e. clay core, vertical chimney/blanket drains and a toe berm – see Figure 1) and constructed (early 1980) across a shallow valley, which had previously been filled with approximately 6 to 8 m of historic tailings.

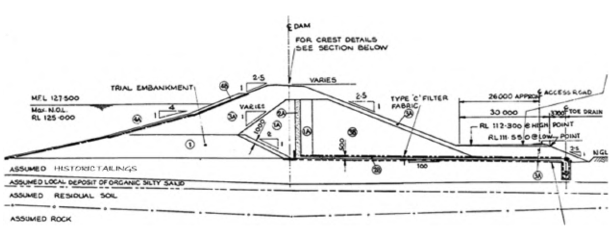

Figure 1. Typical Dam Cross Section.

The critical dam length across the valley is approximately 800 m with a maximum embankment crest height of 26 m and associated toe berm height of approximately 7 m.

Several site investigations were completed to provide supporting information for the stabilisation design. The site investigation information along with historical records were used to develop a three-dimensional (3D) ground model of the site for use in design assessments.

2 Site investigation

Five separate site investigations were completed over a four-year period to gain sufficient information to inform the stabilisation design. The investigations comprised the following in situ testing: cone penetration tests (CPTs), boreholes (BH), test pits (TP), vane shear tests (VST) and ball penetrometer tests (BPT). Table 1 shows a breakdown per site investigation for the key tests that were used to build the 3D ground model.

Table 1. Site investigation summary

Site Investigation	CPT	BH	TP
SI1	19	8	2
SI2	64	14	13
SI3	12	15	20
SI4	79	-	-
SI5	32	-	-
Total	**206**	**37**	**35**

3 Data interpretation

3.1 Overview

All available CPT data were processed to identify different material behaviours, generally based on the following features: corrected tip resistance (q_t), sleeve friction resistance (f_s), pore water pressure ratio (B_q), state parameter (ψ) and soil behaviour type index (I_c).

Both q_t and B_q were calculated consistent with typical CPT data processing, as described in Robertson & Cabal (2022). The state parameter (ψ) was calculated consistent with recommendations by Jefferies and Been (2016) using both the screening level methods proposed by Plewes et al (1992) and Been and Jefferies (1992) to estimate λ_{10} (i.e. the slope of the critical state line in e-logp' space). The critical state parameter M_{tc} was selected based on available triaxial test data. The soil behaviour type index (I_c) was calculated consistent with the method proposed by Roberston (2009).

Each CPT interpretation was compared with information from the nearest borehole using a purpose-built python code. This information was manually reviewed in an iterative process to delineate each geotechnical unit until appropriate alignment was reached between nearby CPTs, BHs and TPs. An example of a crest CPT/BH comparison is shown in Figure 2.

3.2 Unit delineation

Through the iterative review of the CPT material behaviours and associated local BHs/TPs, nine separate geotechnical units were defined as follows:

- Topsoil/Cover: fill placed on top of the historic tailings at the toe and on top of the tailings within the basin, 0.20–0.50 m thick. Entail higher q_t and f_s than the underlying material.

- Tailings: material found within the basin upstream of the main embankment. Generally characterised with a q_t between 2 and 6 MPa, f_s between 70 and 120 kPa, B_q near 0. State parameters suggests a dilative behaviour, likely biased by partial saturation or slight cementation. The low variability of its parameters allows for clear differentiation from the underlying embankment fill or historic tailings.

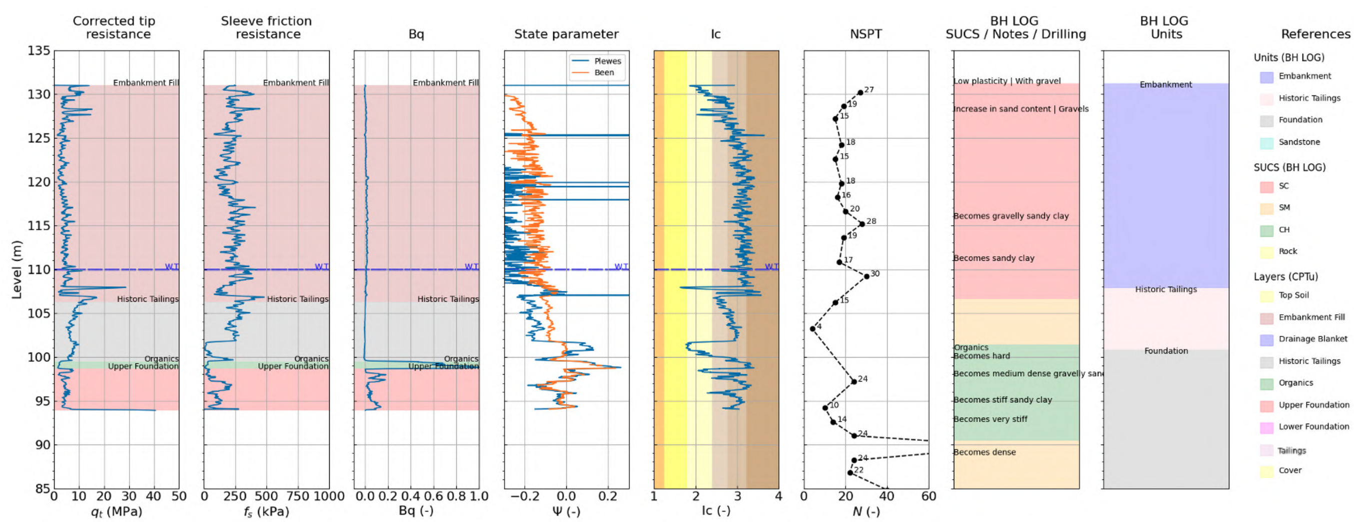

Figure 2. Example of layer identification using CPTu and BH logs located at the dam crest.

- Embankment Fill: clay-like fill material used for the construction of the main embankment. Generally characterised with a q_t close to 5 MPa, f_s between 150 and 350 kPa and B_q near 0.

- Drainage Blanket: sand-like material located under the toe berm, between the embankment (i.e. toe berm) fill and the historic tailings. Generally characterised by a local spike in the q_t.

- Historic tailings: located below the embankment and the tailings and extends laterally across the majority of the dam area. It has q_t between 5 and 10 MPa, f_s between 0 and 300 kPa, uniform B_q near 0, and a screening level state parameter suggesting dilative behaviour on the upper portion, likely affected by partial saturation or cementation.

- Organics: clayey layer located below the historic tailings and corresponding to the natural ground surface before the construction of the dam; note that some borehole logs depict the presence of roots. In CPTu logs, this layer is identified by its low strength and a high spike in B_q.

- Upper Alluvium: clay-like layer with gravels found below the Organics layer. It has a low strength matrix interbedded with lenses of a higher strength (probably gravels), and $B_q > 0$. It can be identified by a slight increase in strength and a reduction in B_q in comparison with the organics layer.

- Lower Alluvium: gravelly clay layer found below the upper alluvium. Identified by a sudden increase in strength, and $B_q < 0$. CPT refusal occurs in this layer.

- Bedrock: hard rock layer. The depth to the bedrock was obtained from the borehole logs.

Of particular significance to the project, the process of unit delineation identified a continuous weak organic unit across the site which had not been previously picked-up by the Engineer of Record (EoR). As noted above, the units behaviour (i.e. low strength and a high spike in B_q within CPTs) was identified in the majority of CPTs across the site at approximately the same elevation (RL). Review of historic records and photographs identified that the valley was not cleared of vegetation prior to the historic tailings deposition, resulting in a continuous layer of organic rich soft clay beneath the tailings.

It is noted that BHs done under the five SIs were drilled using the wash boring method, which can explain why the nature of this unit was not well identified at the time of drilling.

Following the unit delineation and specific identification of the organic unit, sonic BHs were drilled to confirm the nature of the unit. As can be observed in Figure 3, the Organic unit suffered severe disturbance during the sonic drilling process, confirming its sensitive and soft nature as identified in the CPTs.

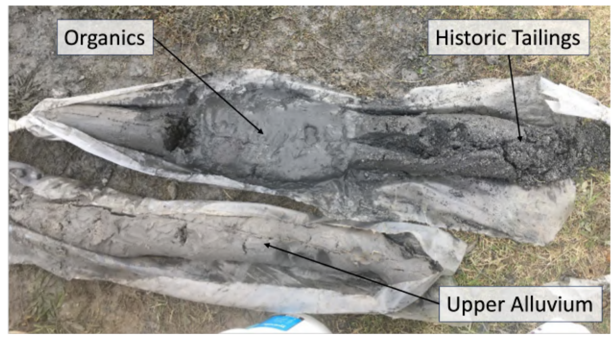

Figure 3. Disturbed samples from BH logs. Organics and Historic Tailings units.

3.3 Unit separation

Following the initial unit delineation, additional consideration was given to subdividing the historic tailings into a coarse and fine fraction, which is observed in the BH/TP logs and particle size distributions.

The Robertson (2009) I_c index was used to subdivide the coarse ($I_c < 2.6$) and fine ($I_c \geq 2.6$) fractions with the f_s also providing a generally consistent delineation between the two fractions; the coarser fraction (referred to as 'historic coarse') entails lower sleeve friction measurements when compared to the fine fraction (referred to as 'historic fine'), as shown in Figure 2, between RL100 m and RL102 m.

The delineation proved to be generally consistent with the expected spatial distribution of the coarse and fine fractions based on review of historic records.

4 Ground model

4.1 Overview

To support the stabilisation design, a 3D ground model was built within the software package Leapfrog Geo, by Seequent (2023). The following data inputs were used to construct the model: i) topographic survey; ii) digitised historic drawings/plans and figures; iii) interpreted CPT data.

4.2 Data inputs

4.2.1 Survey and historic plans

Recent topographic Lidar survey representing the existing dam configuration was inputted into the model to represent the upper surface.

Images of the original topographic survey of the valley (prior to tailings deposition) and containment embankments for the historic tailings deposition were digitised to aid in the interpretation of units and distribution of historic tailings.

Issued for construction drawings were used to develop a 3D model in Autodesk Civil 3D of the dam and its inner zoning (i.e. trial embankment, core, chimney, blanket and toe drain). This information was incorporated into the ground model to allow sections to be cut at any chainage for design analyses.

4.2.2 CPT

Interpreted data from CPT tests was imported in Leapfrog Geo as Drillhole data, composed of the following tables: i) Collar: ID and coordinates for each sounding; ii) Survey: trajectory of the sounding (vertical for the CPT); iii) Intervals: categoric or numeric intervals data in a "from-to" depth format.

The most relevant intervals data for the ground model are the discrete interpreted units for each CPT location (i.e. Topsoil/Cover, Tailings, Embankment Fill, Drainage Blanket, Historic Tailings Coarse/Fine, Organics, Upper Alluvium, Lower Alluvium, Bedrock) and the supporting CPT interpretation data (i.e. q_t, f_s, B_q, ψ and I_c).

4.3 Model construction

Leapfrog Geo creates surfaces using a mathematical algorithm based on the Radial Basis Function (RBF) for interpolation and extrapolation. The RBF algorithm models the known data and can provide an estimate for unknown points. This estimation is based on the closeness to the known data, the redundancy between data, and the variogram.

Three dimensional (3D) surfaces for each geotechnical unit were modelled using the discrete interpretations from CPTs. Most of these surfaces were modelled as sheet-like "deposits" defined by the contact points between underlying and/or overlying units. Additionally, the geometry of the main embankment and the drainage system (as recreated using the available design drawings) were input as 3D designs in the model. The bedrock unit was modelled using borehole data, as the CPTs sounding did not reach this unit.

These surfaces were built in stages beginning with the bedrock and ending with the cover, as seen in Figure 4. This outcome was extremely valuable to understand the lateral extent of the most unfavourable units along the valley.

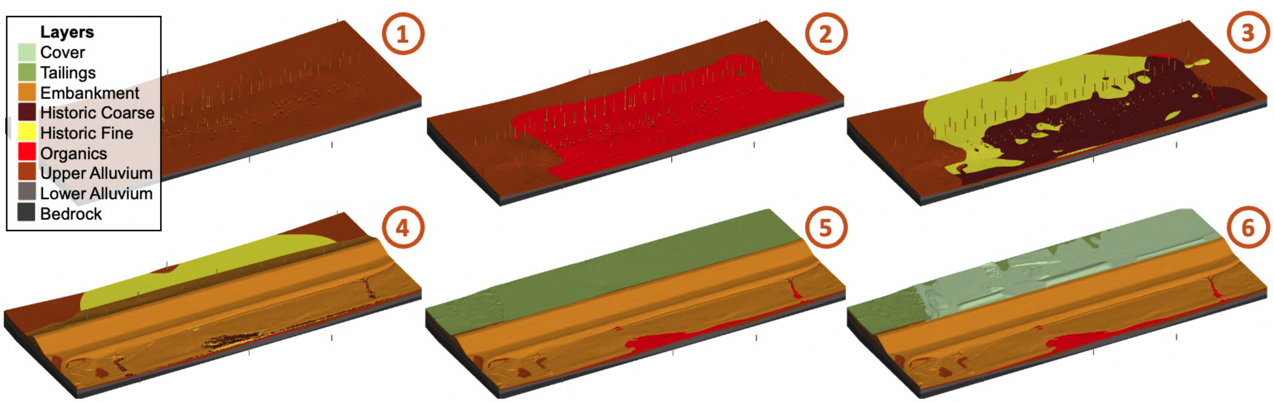

Figure 4. 3D Ground Model showing the main deposition/construction stages

4.4 Model use

A substantive upfront effort was required to development the 3D ground model for the dam and its foundation. However, obtaining transverse and longitudinal cross-section though the resulting ground model (as illustrated in Figure 5 and 6) was very valuable to interrogate the full project extent, identify critical areas (i.e. thickest zone of historic tailings/organic) and allowed sections to be cut at any location.

In addition, as the model was developed in Leapfrog Geo, it allowed for the seamless transfer of sections into associated analyses software packages (i.e. GeoStudio and Plaxis). The ability to rapidly develop analyses section proved invaluable to the stabilisation design.

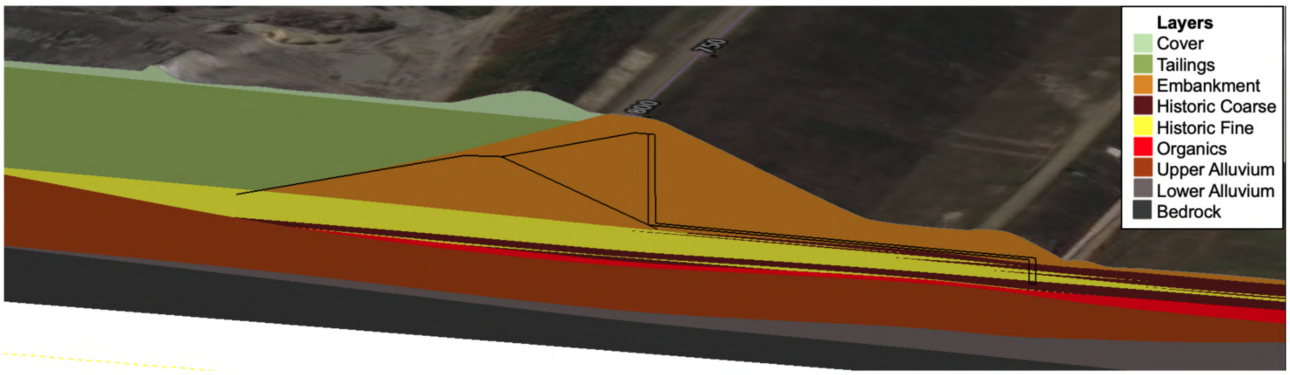

Figure 5. Example of a transversal cross-section along the center of the dam

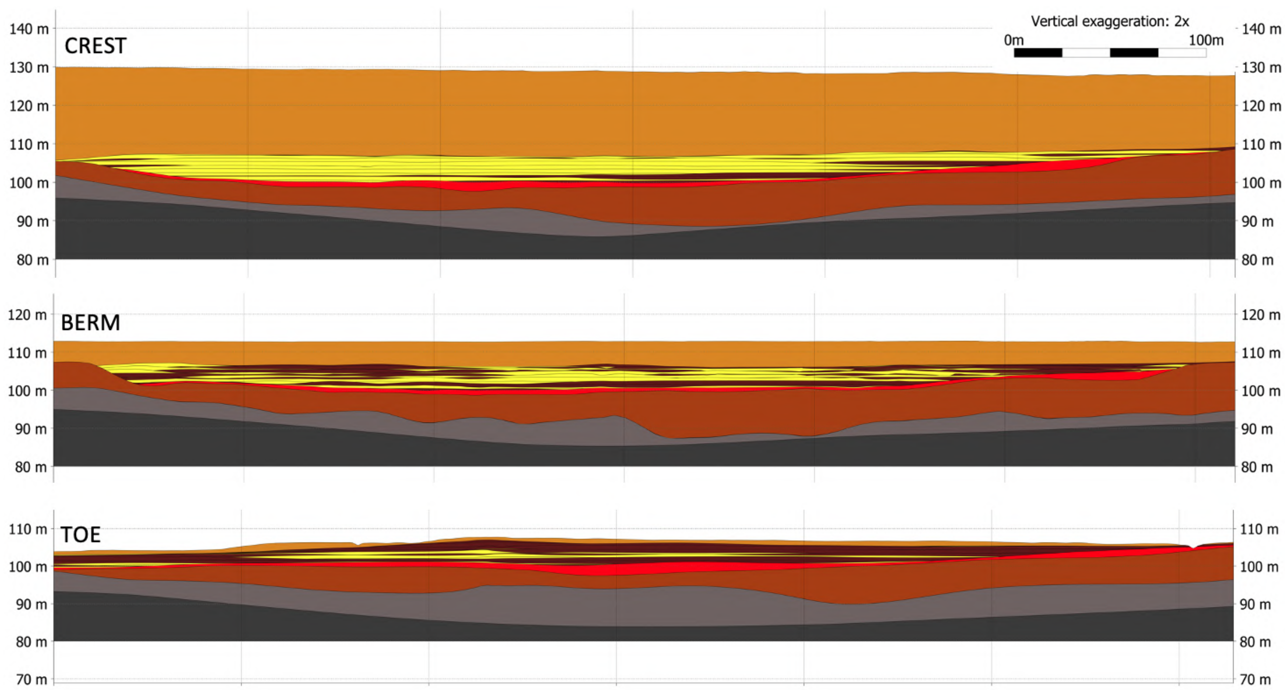

Figure 6. Example of a longitudinal cross-section along the dam crest, berm and toe

5 Conclusions

A comprehensive three-dimensional (3D) ground model was developed to design the stabilisation of a dam founded on both weak and liquefiable units up to about 18 m below ground surface.

Spanning an area of about 800 meters, the ground model was built through a combination of in-situ tests and the digitization/georeferencing of historical drawings and plans. The investigations comprises 206 cone penetration tests (CPTs), 37 boreholes (BH), and 36 test pits (TP); moreover, various additional tests were available, such as: vane shear tests, ball penetrometer tests, and sampling.

CPT data were rigorously processed to discern distinct material behaviors based on parameters such as corrected tip resistance (q_t), sleeve friction resistance (f_s), pore water pressure ratio (B_q), state parameter (ψ), and soil behavior type index (I_c). Each CPT interpretation was meticulously compared with information from the nearest borehole using a specially developed python code, followed by manual review and iterative refinement to delineate the different geotechnical units based on CPT response and physical logs.

This meticulous process uncovered a continuous weak organic layer across the site, previously overlooked by the Engineer of Record (EoR). Ultimately, nine distinct geotechnical units were identified, with one being further subdivided based on its CPT response and grain size.

The 3D ground model, constructed using Seequent Leapfrog Geo, incorporated unit levels specified from each CPT, digitized historical drawings/plans, and a topographic survey. Details of the final model were presented in terms of 3D volumes and representative transversal/longitudinal cross-sections that are used for design stages.

Acknowledgements

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