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Non-linear straining of foundation soils in the progressive failure of the Mount Polley TSF embankment

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1 INTRODUCTION

On August 4, 2014, a breach occurred in the perimeter embankment at the Mount Polley Tailings Storage Facility (TSF) in British Columbia, Canada, causing a spill of mining waste into the environment. This event received extensive news coverage and triggered an unprecedented level of industry reviews and evaluations. The Government of British Columbia, together with the Williams Lake Indian Band and the Soda Creek Indian Band, established an Independent Expert Engineering Investigation and Review Panel (IRP or Panel) to determine the cause of failure.

The breach was sudden and without observable precursors. During the embankment collapse, the mass of soil underwent a rotational-translational movement involving large horizontal displacements in a foundation unit ~10m below the original ground level. The slippage at the base took place in a thin (≤2m) varved clay deposit designated as the "Upper Glaciolacustrine Unit", or the Upper GLU. The IRP (2015) made a determination that undrained strengths controlled this unit's mechanical behavior during failure. Furthermore, the clay's strain-weakening properties made it susceptible to progressive failure. The Panel found that the breach occurred when the peak undrained shear strength of this material was exceeded. These findings were supported by two-dimensional static and deformation analyses that suggested that average strengths slightly below peak values were acting at failure in the Upper GLU. A cursory three-dimensional static analysis found that substantial three-dimensional stability effects were present in the failure that merit an explanation.

2 PROBLEM STATEMENT

A detailed three-dimensional static analysis demonstrated that, due to large amounts of shearing resistance available in the shell and upper tills along the sides of the slide (the so-called "three-dimensional stability effects"), the entire Upper GLU area involved in failure would have to fully weaken in order to bring the soil mass to a limiting equilibrium.

Such a finding brought into focus the question of pre-collapse deformation levels. Laboratory tests indicate that shear strains in excess of 60% would be required for the unit to fully weaken (KCB 2015); in a 2m deposit, this may translate into lateral deformations in the order of 1.2m prior to collapse. From the brittle nature of this failure we know that no such deformations had taken place.

To reconcile the apparent incompatibility of field observations, conclusions suggested by three-dimensional static analyses, and laboratory testing results, it has been posited that the Upper GLU acted as a layered system rather than a uniform block, straining non-linearly throughout its thickness. A hypothesis has been put forward that a thin layer of Upper GLU material strained more severely than the rest of this stratum, fully weakening in the process, but without accruing significant deformations (Zabolotnii 2020, Ch.2).

3 METHOD

The failure at Mount Polley was evaluated using three-dimensional deformation analysis. *FLAC3D* (Itasca 2017) was identified as a suitable vehicle for the task due to its customizable constitutive models and competent handling of post-peak plasticity. A three-dimensional model of the failure location (in Fig. 1) was developed from available topography maps, soil profiles assembled by KCB (2015) and IRP (2015), and pre- and post-collapse borehole records. Core constitutive models were customized with the use of *FISH* functions to emulate the soils' stress-strain and deformation behaviors of interest in the manner reported by Zabolotnii (2020, Ch.3), and calibrated against laboratory data reported by the two investigators.

The model was built incrementally in nine steps to emulate the staged construction of embankment and track the evolution of key characteristics throughout the progression of this failure. Scale effects were investigated using three models with varying resolutions. An upper and a lower bound analysis were conducted to test the variation in simulated predictions under two extreme assumptions, that of "no strain-weakening" and that of "instant full weakening."

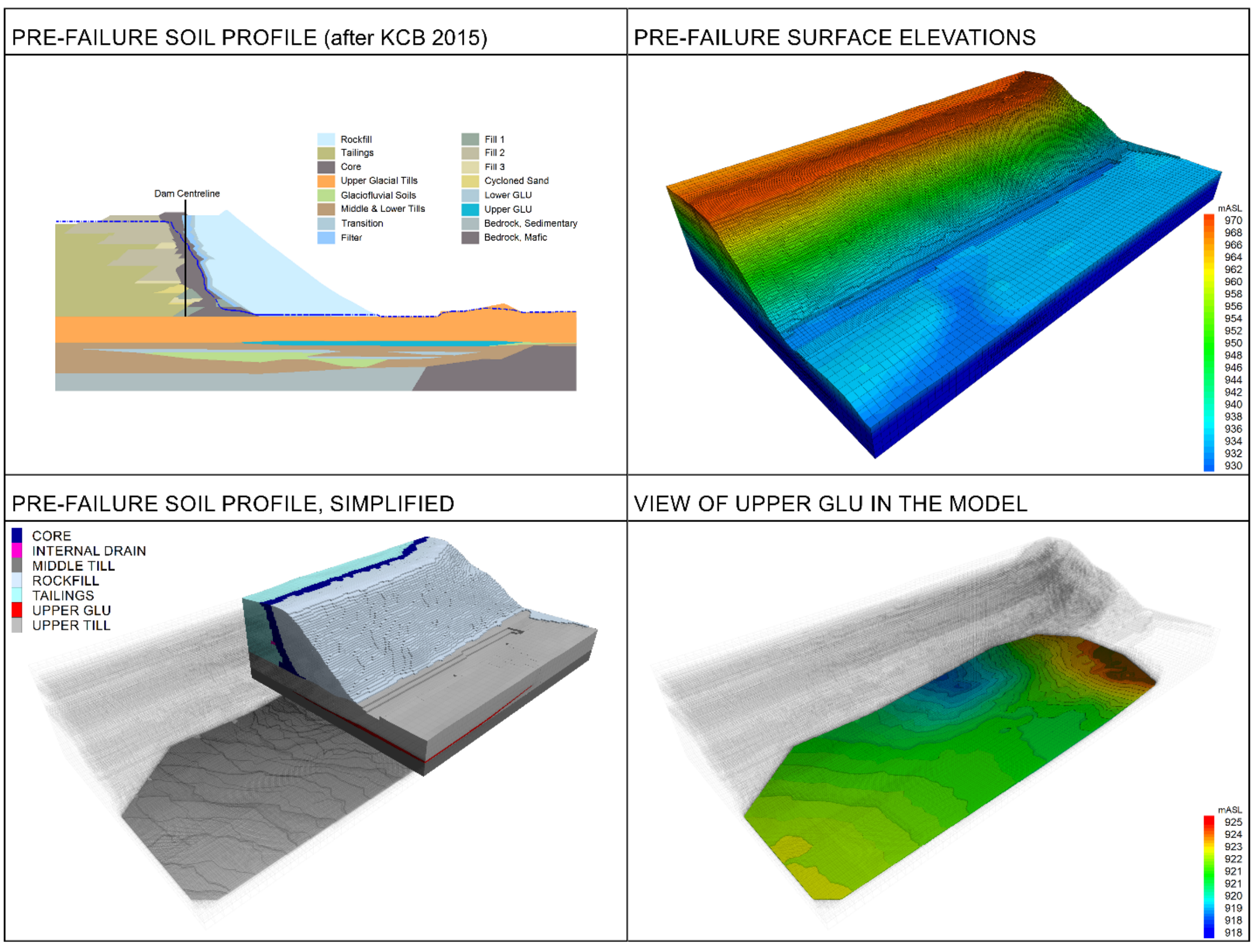

Figure 1. The model of Mount Polley TSF at the failure location. Clockwise from top left: soil profile at the slide midpoint (based on a reconstructed soil profile by KCB 2015, Fig. 2.6); *FLAC3D* model of the failure location with pre-collapse surface elevations; Upper GLU's extent, relative location in the model, and elevations of top interface; simplified soil profile of failure location used in the deformation analysis.

4 PROGRESSION OF FAILURE

Our simulation results indicate that throughout the construction of embankment, the Upper GLU behaved as a layered system whereby a thin soil band at or close to the base of the unit (seen in Fig. 2) strained more than the adjacent materials; this process was exacerbated by the onset of strain-weakening. In the model, a plastic yield zone had materialized in this band as early as two or three years prior to collapse. The zone propagated with each addition of new embankment material, but remained contained until the summer of 2014.

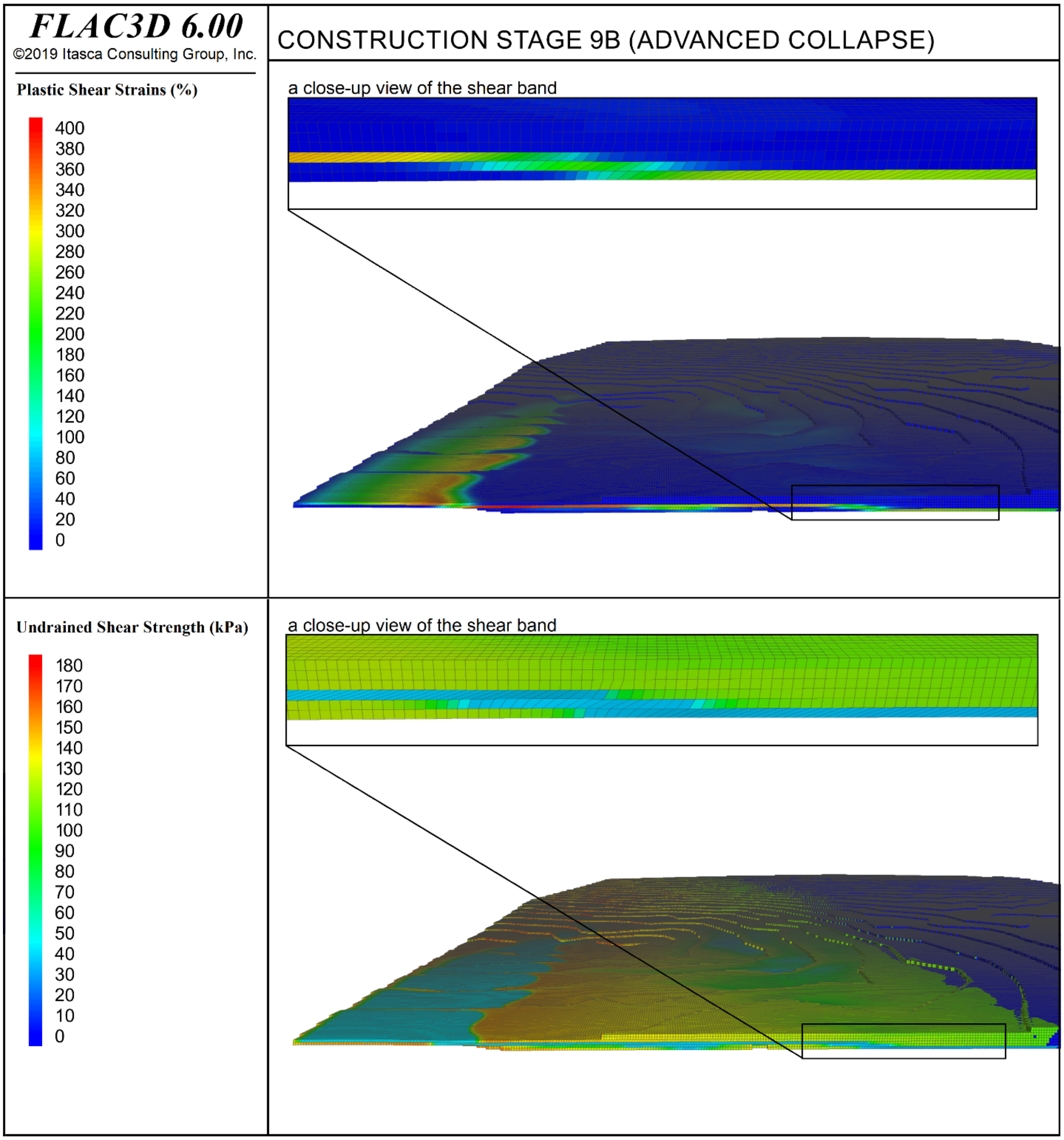

Figure 2. A cross-sectional view of the Upper GLU passing through the slide middle showing plastic shear strains (top) and undrained shear strengths (bottom) in the Upper GLU during stage 9B at an advanced point of collapse.

On August 4, 2014, a specific chain of events unfolded that led to the catastrophic collapse of the structure. The onset of collapse was precipitated by the emergence of a number of critical conditions in the foundation, all fundamentally triggered by the non-linear straining processes in the Upper GLU. In a thin shear band, a considerable loss of shear resistance to weakening took place at negligible shear displacements. As a result, a substantial area in the Upper GLU weakened nearly without deforming. A lack of deformation response in the overall soil mass to the weakening of the foundation translated into a lack of mobilized shear resistance. Our analyses show that the embankment ultimately failed due to an asynchronous mobilization of aggregate strengths in the overall soil mass combined with a rapid and extensive weakening of the foundation (Zabolotnii 2020, Ch.6). The extent of weakening in the foundation during collapse can be appreciated from Figure 2, bottom, showing shear strengths in the shear band and adjacent Upper GLU material.

5 SHEAR BAND THICKNESS

Due to the discrete nature of modelling in *FLAC3D*, the shear band thickness predicted in a simulation is controlled by the height of zones. This limitation is rooted in the absence in our constitutive models of material parameters with the dimension of length, so that the thickness of the shear band remains undefined (Vardoulakis & Sulem 1995, p.10). As a result, simulation alone cannot be used to determine the thickness of a shear band.

Pronounced scale effects were noted in the simulation of failure at Mount Polley. Our coarsest and intermediate models, with zone heights of 50 and 25cm in the area of the Upper GLU, failed to correctly replicate failure, remaining stable. In contrast, the model with the finest mesh, with zone heights of 12.5cm in the region of the Upper GLU, correctly replicated the failure events. We surmise from such outcome that the actual thickness of the shear band is closer to 12.5 cm than it is to 50 or 25 cm.

The results of the upper and lower bound analyses indicate that some discretization error is present in our finest analysis, suggesting an actual shear band thickness <12.5cm. The lower bound analysis additionally demonstrates that the shear band thickness is greater than zero. In the context of the sub-horizontal varved macrostructure of this glaciolacustrine deposit we submit that the true thickness of the shear band was probably between 1 and 3cm.

6 CONCLUSIONS

In the progressive failure at the Mount Polley TSF, the Upper GLU acted as a layered system, straining non-linearly in response to loading. A thin band of soil in this unit accrued significant amounts of shear strain, weakening in the process. The plastic yield zone that developed in this shear band controlled the stability of the entire structure, creating the conditions that ultimately triggered collapse.

As the yield zone propagated through a thin band rather than through the unit's full thickness, the deformation levels prior to collapse were minor; such deformation behavior explains a lack of observable precursors. The actual thickness of the shear band is thought to have been between 1 and 3cm.

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