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Estimating shear stress within a clay foundation using the Burgers-creep model

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1 INTRODUCTION

A currently operating tailings storage facility (TSF) was constructed on foundations consisting of, in descending stratigraphical order, a 3 m clay unit, a 5 to 10 m thick permeable gravel unit, a 1.5 m sand and silt unit, and a medium plastic clay unit (Lower Clay) that extends over 100 m in depth to bedrock. The TSF embankment is approximately 20 m tall and was constructed by raising annually. Slope inclinometers were installed at multiple locations along the embankment once construction neared the final crest elevation and during subsequent periodic site investigations. These inclinometers are currently showing constant-rate creep deformations within the Lower Clay.

Creep can occur in three stages. Primary creep occurs when the strain rate decreases with time, secondary creep occurs when the strain rate becomes constant, and tertiary creep occurs when the strain rate begins increasing exponentially resulting in failure known as creep rupture (Lacasse & Berre 2005). The potential for creep rupture can be evaluated by comparing shear stress within the foundations to the upper yield strength, which is defined as the shear strength associated with the minimum strain rate at which creep rupture occurs (Finn & Shead 1973). A *FLAC* model was constructed to estimate the shear stress distribution within the Lower Clay. The clay was modeled using the Burgers-creep viscoplastic constitutive model, and the *FLAC* model was calibrated against the slope inclinometer data. The modeled shear stress distribution will be compared to the upper yield strength of the material on completion of the laboratory testing underway to evaluate the potential for creep rupture. This abstract describes the construction of the *FLAC* model and calibration of the Burgers model viscous properties.

2 MODEL CALIBRATION

2.1 *Inclinometer data*

Slope inclinometers are installed at the embankment crest and toe, along planes of instrumentation for monitoring purposes. The inclinometer A0 or A+ direction, representing the expected greatest direction of movement, are positioned perpendicular to the embankment crest. Model calibration was performed against the inclinometer showing the greatest displacements and with the longest period of record. The selected inclinometer is located at the toe of the embankment and was installed shortly prior to the end of construction. Manual readings of this inclinometer were taken at 0.5 m depth intervals once per year for the first three years before increasing in frequency to approximately once per quarter. The inclinometer data suggests creep is occurring within the top 30 m of the Lower Clay unit. Displacement versus time plots indicate that clay was undergoing primary creep for approximately three years before transitioning to secondary creep, where it is now.

2.2 *Burgers-creep model*

The Burgers-creep viscoplastic constitutive model was selected to model the Lower Clay as it can be calibrated relatively easily to model the observed deformations. The constitutive model comprises visco-elastic strain-rate behavior and plastic strain-rate behavior, acting in series. The visco-elastic constitutive law corresponds to a Burgers model and the plastic constitutive law corresponds to a Mohr-Coulomb model.

The Burgers model comprises a Maxwell model and Kelvin model acting in series. The Maxwell model consists of a spring and dashpot in series. Under constant stress the Maxwell model will undergo elastic deformation and strain at a constant rate. The elastic shear modulus, G^M, controls the elastic deformation while the Maxwell viscosity, η^M, controls the strain rate. The Kelvin model consists of a spring and dashpot in parallel. Under constant stress the Kelvin model will strain at a decreasing rate until it reaches a horizontal asymptote when time tends towards infinity. The Kelvin shear modulus, G^K, controls the asymptotic value, while the Kelvin viscosity, η^K, controls the strain rate. The strain experienced by the Burgers model is the sum of the strains from the Maxwell model and Kelvin model (Findley et al. 1976).

2.3 *FLAC model calibration*

Prior to calibration, the *FLAC* model was brought to static equilibrium with all units assigned the Mohr-Coulomb constitutive model. The model was discretized into 2 m by 2 m quadrilateral zones. Fixed bottom and roller side boundary conditions were used. The bottom model boundary corresponds to the base of where creep was observed. Using gravity loading, the model was first brought to equilibrium without the TSF, representing the stress state under original ground conditions. Zones representing the TSF embankment and tailings deposit were then added, and the model solved to equilibrium again. Displacements were subsequently zeroed and the Burgers-creep viscoplastic model was assigned to the Lower Clay to begin the calibration.

Calibration began with the Maxwell component of the Burgers model. The inclinometer does not capture the elastic response, so the elastic shear modulus was derived from pressuremeter tests conducted during a site investigation. The Maxwell viscosity was isolated by setting the Kelvin viscosity as infinite and the Kelvin shear modulus as zero, then calibrated to the rate of displacement observed during secondary creep.

The Kelvin shear modulus was then calibrated to the asymptote value. This was derived by linearly extrapolating the secondary creep portion of the displacement-time inclinometer curve to the y-axis. During this part of the calibration, the Maxwell viscosity was set as infinite to negate its strain component and the Kelvin viscosity was minimized to allow the model to more quickly reach the asymptotic value.

Finally, the *FLAC* model was calibrated to the entire inclinometer record by comparing displacements against depth along the inclinometer string as well as displacements against time at select sensors. The calibrated Maxwell viscosity and Kelvin shear modulus values were assigned to the corresponding parameters of the Burgers-creep viscoplastic model and the Kelvin viscosity was calibrated to match the recorded displacements from the inclinometer time series.

3 RESULTS AND DISCUSSION

The final calibration was performed over an 11-year model time period. Each mechanical step was performed for 300 seconds of creep. The calibrated results (Fig. 1) show good agreement with the inclinometer data, both with depth and with time. This is despite the limitation of this analysis; in that it does not consider the role of consolidation and the dissipation of excess pore pressures from embankment construction in the initiation of creep.

The calibrated Burgers-creep viscoplastic model viscous properties are listed in Table 1. The effective shear stress under the TSF embankment in the model ranges from approximately 15 kPa at the top of the Lower Clay unit to approximately 70 kPa approaching the bottom contact of the creeping zone.

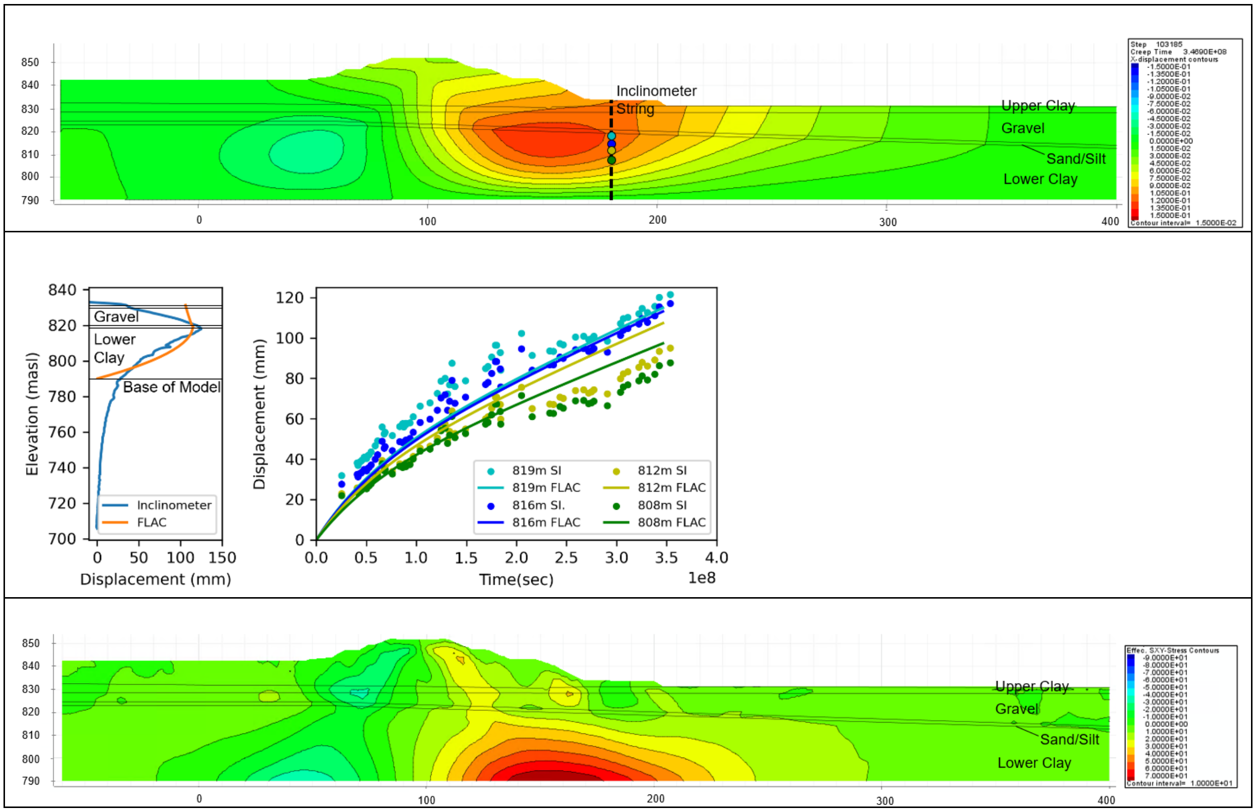

Figure 1. Calibrated model results showing the modeled horizontal displacements (top), displacements compared against slope inclinometer data (middle), and modeled effective shear stress distribution (bottom).

Table 1. Calibrated Burgers-creep model viscous properties

Property	Value
Maxwell viscosity, η^M	2e12 kPa·sec
Kelvin shear modulus, G^K	1.2e4 kPa
Kelvin viscosity, η^K	1e12 kPa·sec

4 CONCLUSIONS

This work demonstrates that the Burgers-creep viscoplastic model can be a simple practical constitutive model for analyzing the creep phenomenon. The constitutive model can be calibrated to readily available displacement data from inclinometers that are often installed as a part of requisite dam safety monitoring programs, as opposed to requiring advanced laboratory testing that requires good quality undisturbed sampling.

In this example, the Burgers-creep viscoplastic model was successfully calibrated against inclinometer data to model the creep behavior of a clay foundation under a TSF using *FLAC*. The analysis allows for a comparison of the modeled shear stress to the upper yield strength obtained through laboratory testing to conduct a preliminary evaluation of the potential for creep rupture of the material.

The *FLAC* model can be further evaluated and refined through single element calibration of the Burgers-creep viscoplastic model to laboratory testing. The calibrated creep model could also be used to potentially estimate future displacements and evaluate how the foundation shear stress distribution will change with time.

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