Two-Dimensional Stability and Seismic Loading Models of Crater Lake Outlet, Mount Ruapehu, New Zealand

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ABSTRACT

Two-dimensional geomechanical modeling of the Crater Lake outlet at Mount Ruapehu, New Zealand uses rock mass strength data to determine the stability of the outlet under seismic loading in order to analyze the risk of outlet failure. The outlet consists of three different rock units: two strong andesitic lava units and a weaker autoclastic breccia unit. The lava units are modeled using data obtained from laboratory strength testing by previous workers, while the highly heterogeneous breccia unit is modeled using the weighted average approach. Finite element analysis using Phase2 by Rocscience is performed to develop a valid model of the outlet. Peak ground acceleration values ranging from 0-0.5g are applied to the model to predict how the outlet will behave mechanically in the event of seismic activity, both due to regional seismicity and volcano-tectonic quakes associated with Ruapehu. The model shows negligible (millimeter-scale) displacements and ultimately predicts that the outlet will remain stable, even in the event of abnormally high seismicity. This study concludes that seismicity alone is not likely to trigger outlet failure and a subsequent lahar at Mt. Ruapehu.

KEYWORDS: Geohazards, rock mass strength, failure analysis, volcanic materials, seismic loading

1. Introduction

Mt. Ruapehu is an active andesitic volcano situated on the Central Plateau of New Zealand's North Island (figure 1) (Kilgour et al. 2010). Between major eruptions, the vent fills with water, forming the Crater Lake (Massey et al. 2010). Mt. Ruapehu attracts year-round tourists for skiing, hiking, and other activities. In the past, Crater Lake's outlet has failed, unleashing a breakout lahar onto the ski fields below and into the Whanagehu River with catastrophic downstream effects (Johnston et al. 2000).

Understanding the geotechnical behavior of the outlet and its potential for failure due to seismicity associated with volcanism is crucial for developing a long-term understanding of volcanic hazards at Ruapehu. Although the outlet is currently stable, limited work has been done to understand how seismic activity could impact the stability of the outlet and potentially lead to failure. The outlet is geologically and therefore geotechnically complex, being comprised of two units of strong andesite lava and a unit of weak, friable breccia (figure 2) (Cook 2015). Previous investigations by Cook (2015) into the stability of the Crater Lake outlet constrained the geotechnical properties of the rock units and developed a schematic model of the outlet.

This investigation utilizes Cook's (2015) data to develop a two-dimensional geotechnical model of the lake outlet and predict its behavior in seismic events. First, this study constructs a model of the outlet under static conditions in order to verify its validity. Seismic loading is introduced to explore how the outlet might behave in seismic events related to volcanism. These scenarios provide constraints on dam failure and subsequent lahars through the analysis of the stability of the Crater Lake outlet in both static and seismically active conditions, furthering the overall understanding of volcanic hazards and risk at Ruapehu.

2. Geologic Setting

Mt. Ruapehu is situated in the Taupo Volcanic Zone (TVZ), a 60 km wide and 200 km long zone of volcanism on New Zealand's North Island (Wilson et al. 1995). It has been active since 2 Ma, and it is currently the most productive and frequently active silicic volcanic system in the world (Wilson et al. 1995). Mt. Ruapehu's largest historic eruptions occurred in 1945 and in 1995-1996 (Johnston et al. 2000). These eruptions were relatively small in volume compared to some of Mt. Ruapehu's major prehistoric eruptions, but they had significant societal impacts (Johnston et al. 2000). The 1945 eruption created a fragile barrier of tephra around Crater Lake (Scott 2013). In 1953, this barrier failed catastrophically due to the refilling of the lake. The lahar travelled down the path of the Whangaehu River, where it destroyed the Tangiwai rail bridge and caused the loss of 151 lives as a result (Johnston et al. 2000). The 1995-96 eruptive sequence created a similar tephra barrier around the lake, which was quickly recognized as a potential lahar hazard (Massey et al. 2010). This lead to the development of the warning system that allowed for successful hazard mitigation during the eventual 2007 dam break lahar (Keys and Green 2008).

The Crater Lake outlet features a roughly 10m high waterfall that flows southward into the Whangaehu River (Cook 2015). A strong, resistive lava unit hereby referred to as the Armored Lava Ledge (ALL) caps the outlet. A unit of lava breccia (LB) outcrops at the face of the waterfall directly beneath the ALL, and sits above another unit of resistive andesitic lava called the Lower Grey Member (LGM) (Figure 2) (Cook 2015).

The outlet is surrounded by volcanic alluvium and remnants of tephra from the 1995-96 eruption sequence.

3. Methodology

This study utilizes Cook's (2015) research and supports this with additional data from existing literature. Cook (2015) undertook a thorough study of geotechnical properties of the rock units that make up the outlet. Cook tested for strength, unit weight, stiffness, and porosity of each unit, but was unable to obtain reliable values for the breccia unit, due to its high heterogeneity. Cook also developed a schematic model of the outlet and the surrounding area.

One of the biggest challenges of modeling the outlet is the difficulty of characterizing the LB unit. Heterogeneous materials like volcanic breccias have posed a challenge to many geotechnical models (Marinos and Hoek 2001). However, a methodology for characterizing volcanic breccias has been set forth by del Potro and Hürlimann (2008). The method uses a "weighted average" approach to model the clasts and the groundmass of the breccia as a single material. This methodology was adopted for modeling the strength of the LB unit at Crater Lake. Although little comment has been made on del Potro and Hürlimann's proposed methodology since its publication in 2008, it is based on thorough empirical calibration and the authors believe it to be suitable for this investigation.

This study uses Phase2 by Rocscience to develop a two-dimensional model of the outlet and perform finite-element analysis using the generalized Hoek-Brown failure criterion. The Hoek-Brown failure criterion was initially introduced in 1980 to estimate the strength of hard rock masses and predict the stress conditions under which they would fail (Hoek 1980). The criterion is defined by the uniaxial compressive strength (UCS) of the intact rock mass, material constants m and s, and the major and minor principal effective stresses. Unlike the widely used Mohr-Coulomb method for predicting rock mass failure, the Hoek-Brown method is non-linear. Experimental data has proven that most rock masses tend to fail in a non-linear manner, and Hoek-Brown is the only failure criterion that accounts for this (Hoek 1980). As the use of the Hoek-Brown failure criterion has become more widespread, it has received frequent updates and is widely used for excavations, slope stability analysis, and other finite-element analyses.

4. Results

4.1 Stability Model Development and Validation

This project first developed a valid stability model of the outlet. Since the outlet is stable under static conditions, it was necessary to create a numerical model that reflected this. The initial model of the outlet had a relatively simple geometry (figure 3) and utilized data from Cook's study and literature (Table 1). However, the model did not showed significant displacement and deformation upon initiation, rendering it invalid. These initial deformations were artifacts of the model being unable to converge on a single solution within the maximum number of allowed iterations (n=50,000). Several adjustments were made in order to allow the model to mathematically converge. First, the breccia unit was expanded and then gradually reduced to its original geometry by progressively reducing the unit weight of the added material in order to simulate natural erosion. Simulating natural erosion allowed the model to stabilize, so that the final stage showed negligible amounts of displacement. While the final model ultimately retains the same geometry as the initial model, adding this intermediate stage of simulated breccia erosion eliminated some non-real displacements from the stability model. Additionally, the discretization density of the model was increased around the exposed faces of the LB, ALL, and LGM units. Increasing discretization density in this area provided more thorough calculations in the most sensitive and important area of the model, and also helped mitigate convergence issues. The final stability model (figure 3) still shows some sub-millimeter-scale displacements, but they are small enough to be considered negligible. In general, centimeter-scale displacements would be required to show true failure. Although the displacements shown in the final stability model are small enough to be considered negligible, they do provide some insight into the areas of the outlet that are under the most stress.

Parameter	**Value**	**Source**
Armored Lava Ledge		
Uniaxial Compressive Strength (UCS)	48 MPa	Cook 2015

Geologic Strength Index (GSI)	75	Cook 2015
Intact Rock Parameter (M_i)	25	Hoek et al. 2002
Young's Modulus	21225 MPa	Calculated from Cook 2015
Unit Weight	16.5 kN/m^3	Cook 2015
Lava Breccia		
UCS	28.8 MPa	Del Potro and Hürlimann 2008
GSI	60	Del Potro and Hürlimann 2008
M_i	19 +/- 5	Hoek et al. 2002
Young's Modulus	2444 MPa	Calculated based on Del Potro and Hürlimann 2008
Unit Weight	14.9 kN/m^3	Calculated based on Del Potro and Hürlimann 2008
Lower Grey Member		
UCS	98.3 MPa	Cook 2015
GSI	70	Cook 2015
M_i	25	Hoek et al. 2002
Young's Modulus	41000 MPa	Cook 2015
Unit Weight	25.2 kN/m^3	Cook 2015

Table 1. *Input parameters used to perform finite element analysis in Phase2.*

4.2 Seismic Loading Application

Following the establishment of a valid stability model, this study applied seismic loading to predict how the outlet could behave in the event of seismicity relating to volcanic activity. The study applied peak ground acceleration (PGA) values of 0.1, 0.2, 0.3 and 0.5g to the model. Although there is no actual PGA data available for Mt. Ruapehu, many authors use values from 0-0.3g to model volcano-associated earthquakes (Moon et al. 2009, Voight et al. 1983). A PGA of 0.5g is considered abnormally high for a volcano-tectonic earthquake and it represents an extreme case (Moon et al. 2009).

At a PGA of 0.3g, the model of the Crater Lake outlet showed sub-millimeter to millimeter-scale displacements within the LB unit and even smaller displacements within the ALL and LGM units (figure 4). When PGA was raised to 0.5g, the displacements increased slightly, but remained within the same order of magnitude.

5. Discussion and Recommendations

For PGA of 0.3g, the model of the outlet (figure 4) shows a negligible amount of displacement, indicating that the risk of the outlet failing in a seismic event is low. Even at a significantly higher PGA of 0.5g, displacements were still on the millimeter scale. Though 0.5g is higher than expected in a volcano-tectonic quake, it's not necessarily a maximum. There is a 10% chance that PGA will exceed 0.5 g in the Tongariro area, due to regional seismicity, in the next 50 years (Stirling et al. 2012). This broad estimate does not consider the Crater Lake vent specifically, and includes all kinds of earthquakes (not exclusively volcano-tectonic quakes). Volcano-tectonic quakes are the biggest source of potential concern in this study due to the outlet's proximity to Ruapehu's vent.

While it is possible that an earthquake with drastically higher PGA could occur and cause outlet failure with a subsequent breakout lahar from Crater Lake, such an event is unlikely. Also not fully understood is the magnitude of volcanic-seismic events at Crater Lake, which may have higher than normal PGAs due to proximity to the erupting vent. Actual PGAs for the Crater Lake vent require further investigation to better constrain the model.

This model has demonstrated that the Crater Lake outlet is not sensitive to seismic loading. Although the outlet is not sensitive to seismicity, history proves that failure is possible for different reasons, but those reasons are outside the scope of this work. As with any active volcanic environment, the hazards at Mt. Ruapehu and its Crater Lake should be continually monitored and reassessed. Future volcanic activity could dramatically reshape the outlet (as it has done in the past) and create an entirely new set of conditions. For example, the addition of another weak tephra layer on top of the ALL unit could put the outlet at great risk, as it did in the years following previous eruptions.

This model could be developed in the future to increase the certainty of this prediction. First and foremost, groundwater data should be incorporated into the model because saturation can greatly affect the mechanical behavior of rocks. Obtaining permeability data for the rock units at the outlet would greatly enhance the model. Additionally, historic, site specific, PGA values for past eruptive events at Mt. Ruapehu could be calculated from existing seismometer data available through GNS to better constrain realistic PGA values for the Crater Lake site.

6. Conclusions

This study is unique as limited work has been done to model the geomechnical behavior of volcanic settings, perhaps due to the difficulty of accessing many volcanic areas as well as the challenge in characterizing heterogeneous units like autoclastic breccias. The model produced in this study utilizes Cook's thorough suite of field data (Cook 2015) along with additional data from literature. This study was undertaken in order to determine whether seismicity could cause outlet failure in order to develop our overall understanding of volcanic hazards at Mt. Ruapehu. Ultimately, the model predicts that the Crater Lake outlet will remain stable even under seismic loading with PGA of up to 0.5g, which indicates that a lahar at Ruapehu due to seismic loading of the outlet is unlikely.

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Appendix

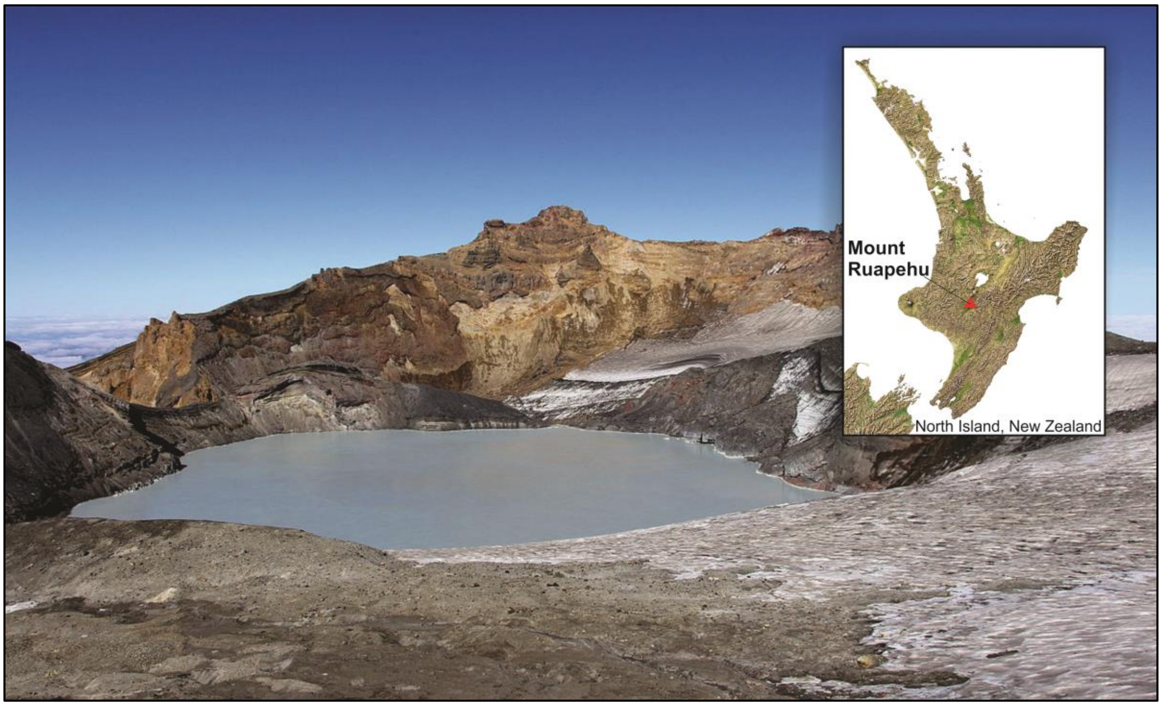

Figure 1. Crater Lake. Inset: Ruapehu's location on the North Island of New Zealand.

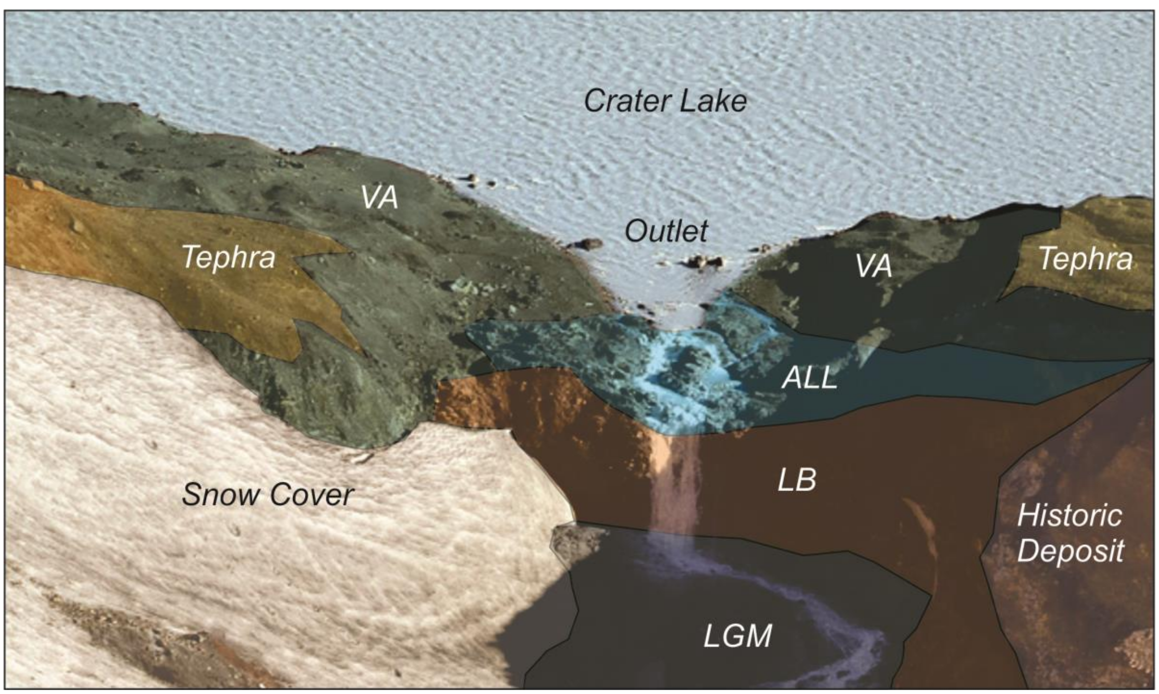

Figure 2. Crater Lake outlet with geologic units shown. The three main outlet units are the ALL, LB, and LGM. Additionally, there are deposits of tephra, volcanic alluvium (VA), and a historic lava flow. The outlet waterfall is roughly 10m high. Photo courtesy of Jaz Morris.

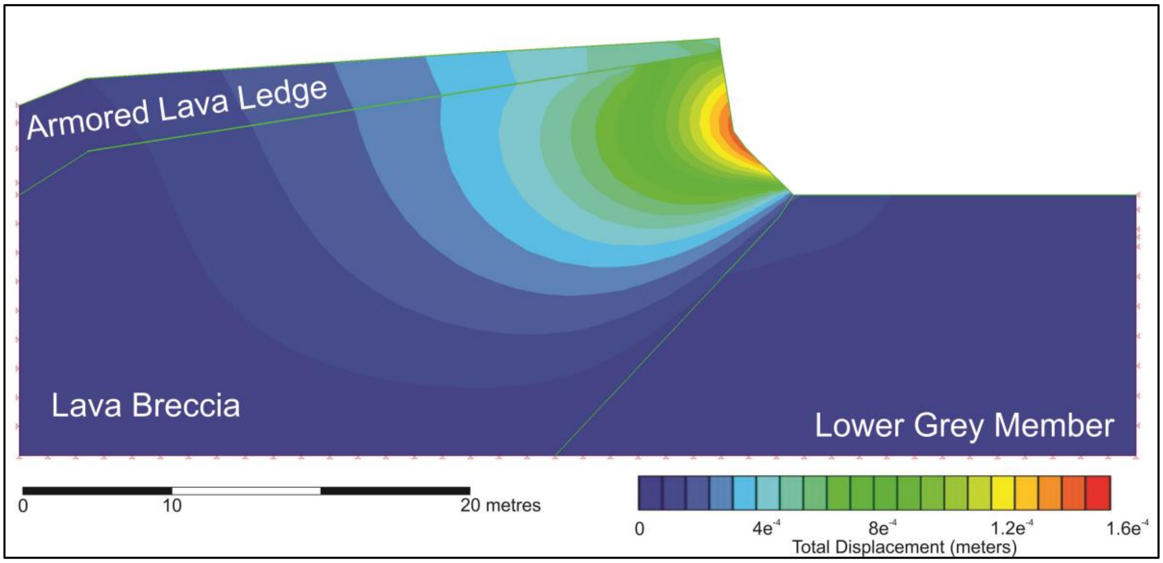

Figure 3. Stability model of the outlet created using Phase2 by Rocscience. This model reflects the outlet under static conditions.

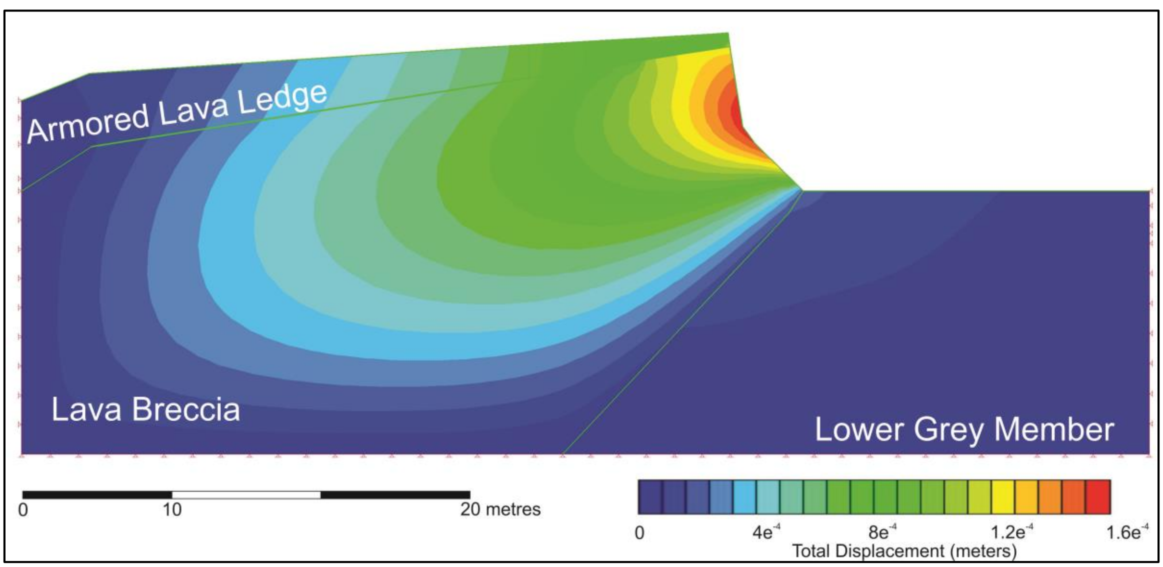

Figure 4. Seismic loading model with a PGA of 0.3g applied.