Numerical modelling of toe buckling deformation in Haast Schist, Central Otago, New Zealand

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ABSTRACT

Toe buckling deformation is an outward expression of strain which develops near the base of a slope in response to induced gravitational and tectonic stresses acting on a rock mass and can lead to kinematic slope instability. This deformation mechanism is considered responsible for anomalously oversteepened foliations identified underlying three deep-seated landslides within schist bedrock of Cromwell Gorge, Central Otago, New Zealand. Spatial and temporal complexities of schist behaviour in response to stress regimes were numerically modelled using Finite Element Methods based on site-specific field (slope and tunnel mapping, borehole logging) and laboratory (UCS, triaxial, indirect-tensile, point load, shear box) testing data. Sequential unloading was incorporated in the model to simulate the evolution of Cromwell Gorge from a low relief surface (Otago Peneplain) to present day topography (1400 m deep). Sensitivity analyses reveal that specific combinations of high locked-in tectonic stresses, foliation stiffness and orientation contributed to the development of flexural toe buckling at the base of Cromwell Gorge.

Keywords: Toe buckling, finite element method, numerical modelling, schist, Cromwell Gorge.

1 INTRODUCTION

Mountains are dynamic environments with shifting stress regimes associated with the formation of valleys due to uplift and erosion. The rock masses that form mountains develop a tectonic imprint of these ongoing stresses by constantly deforming to relieve stress in an attempt to reach equilibrium, often via creeping mass movements on a mountain range scale. As valleys deepen, orientation of principal stress axes progressively rotate, migrating toward the summit. Where these principal stresses coincide with anisotropic weaknesses within a rock mass, gravitational sagging may result in an outward expression of deformation concentrated at the toe of the slope, in the form of toe buckling. Variations of toe buckling deformation comprise curvilinear flexural buckling and three hinge buckling (see Cavers, 1981). This type of deformation is identified globally in a wide range of environments as a result of anthropogenic infrastructure such as road cuttings and open pit mines (Hu and Cruden 1993; Stead and Eberhardt 1997), natural large scale landslides associated with deep seated gravitational slope deformations (DSGSD) (Agliardi et al. 2001), as well as precursors to coseismic landslides such as the 1999 Chi Chi earthquake in Taiwan (Wang et al. 2003). It is therefore important to understand mechanisms governing toe buckling to assist with early hazard identification and comprehension of these large scale slides

Anomalously oversteepened foliations were identified beneath three large scale landslide complexes within Cromwell Gorge, Central Otago, in New Zealand’s South Island. A pertinent research question arose, as to whether these deformations represented a form of toe buckling which developed in response to induced gravitational stresses associated with valley deepening, or whether these structural features were related to metamorphic processes predating the development of Cromwell Gorge. Numerical models simulating rock mass conditions can be utilised to answer this research question. This is possible due to recent advancements in computing technology, which permit realistic simulations of rock mass behaviour in response to induced stress through numerical modelling. Complex algorithms related to constitutive models constrain the behavioural response of the rock mass to various stress states. Both continuum and discontinuum numerical models have been successful in simulating deformations associated with DSGSD and toe buckling (Tommasi et al. 2009; Pereira and Lana 2013), and a continuum approach was selected for this research.

2 BACKGROUND

Extensive geotechnical investigations were carried out in several phases between 1975 and 1992, for the Clyde Power Station project in Central Otago. During this investigation seventeen major landslides within Lake Dunstan catchment were identified (Figure 1). Field mapping, borehole coring and excavation of exploration tunnels within this region indicated Cromwell Gorge generally comprises Rakaia Terrane Schists inclined at an average angle of 20° to 40° towards the southwest. However, anomalous oversteepened to overturned foliations were identified beneath the slide bases of three landslides, namely Nine Mile, No. 5 Creek and Dunlays Slides located on the Dunstan flank of the gorge (Beetham et al. 1991). Bedrock in this area is deformed with schistosity exhibiting flexural buckling steepening upwards toward the slide base at angles from 50° to 90° to completely overturned (Figure 2).

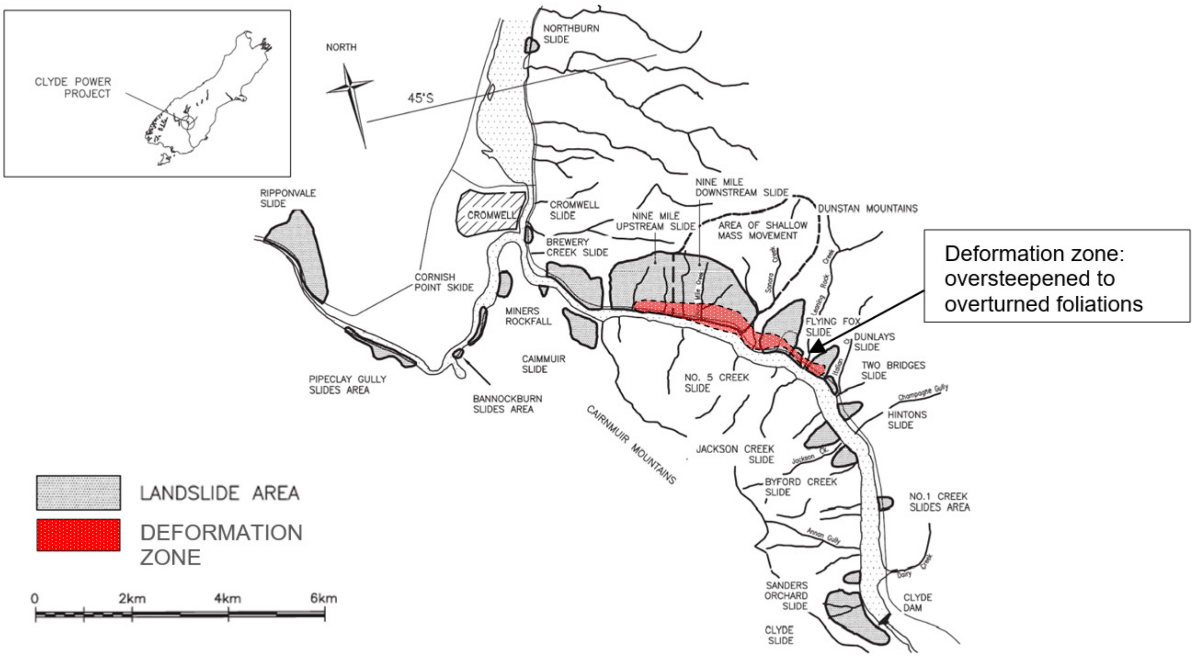

Figure 1. Locality map of Cromwell Gorge depicting approximate locations of major landslides within Lake Dunstan catchment (modifed from Macfarlane 2009).

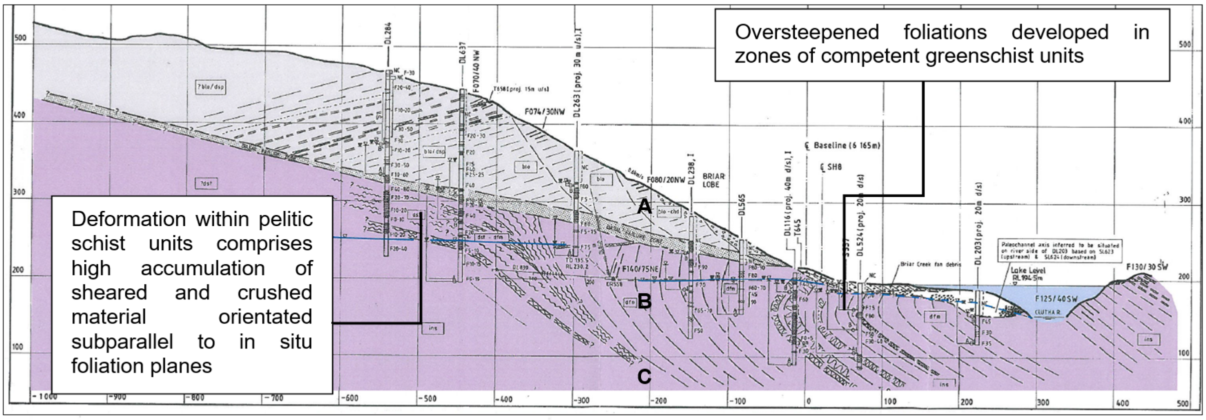

Figure 2. Inferred geological cross section of Nine Mile Slide illustrating three major lithological subdivisions, namely the upper landslide debris and associated basal shear zone (A) directly overlying a zone of deformation (B) which progressively grades into in situ bedrock (C) (from Macfarlane 2010).

3 GEOLOGY AND GEOMORPHOLOGY

The Dunstan flank of Cromwell Gorge is underlain by Rakaia Terrane Schist bedrock characterised by a pervasive schistosity orientated with a general dip of 20° to 40° towards Lake Dunstan. Lithological variations of schist comprise predominantly greyschist ranging from pelitic (micaceous-rich) to psammitic (quartzofeldspathic-rich) end members with subordinate greenschist units. Central Otago is defined by a complex geological history comprising multiple deformation phases which imparted residual impacts on the rock mass of Cromwell Gorge, exhibited by compressional structures (mesoscopic folds) and extensional features (subparallel foliation shears) (Deckert et al. 2002). Preferential foliation planes impose an anisotropic behaviour of the rock mass in response to stress, defined by average anisotropic index ratios of 1.7 and 2.0 for greenschist and greyschist, respectively.

4 NUMERICAL MODELLING

4.1 Objectives

Deformation observed within Cromwell Gorge is considered to be the result of time-dependent rheological anamorphosis of the rock mass in response to accumulation of strain. Strain accumulated during the evolution of Cromwell Gorge, initiating from the Miocene low relief Waipounamu Erosion Surface (Otago peneplain) (Bishop 1994) progressively deepening through fluvial erosion and uplift (McSaveney et al. 1992). Increasing topographic relief is believed to have induced localised rotation of principal stress axes near the slope surface which coincided with the anisotropic rock mass plane of weakness (schistosity). Induced stresses were compounded by high horizontal far field tectonic stresses associated with the obliquely convergent stress regime of the ongoing Kaikoura Orogeny to produce the deformation observed at the toe of the Dunstan flank.

The primary objective of this study is to numerically simulate the rock mass response to induced stresses associated with progressive deepening of Cromwell Gorge commencing from a relatively low relief surface to present day topography (i.e. the 1400 m deep gorge). Results of the numerical simulation are compared to deformation observed beneath the slide bases of Nine Mile, No. 5 Creek and Dunlays Slides to gain an understanding of processes governing deformation mechanisms.

4.2 Methodology

Rocscience 2D Phase^2 program, a continuum, finite element method (FEM), was used to model the anisotropic nature of the schist rock mass by incorporating an elasto-plastic Mohr-Coulomb algorithm with an explicit joint network. The initiating model is based on the relatively level Otago Peneplain which is subjected to sequential unloading to simulate progressive valley deepening through fluvial erosion and uplift. Sensitivity analyses were undertaken to determine the major contributing parameters governing buckling deformation observed at the base of the Dunstan Mountain Range within Cromwell Gorge. Eighty three FEM models were processed by consecutively varying one parameter at time. Parameters varied in the models consists of rock mass properties, foliations orientations, number of stages taken to incise the valley to present day topography, topographic loading and relief, locked in tectonic stresses, seismic shaking as well as hydraulic conditions.

4.3 Boundary conditions and field stresses

Sequential unloading (Figure 3) commencing from the Otago Peneplain was developed by subdividing the geometric attributes of Cromwell Gorge evolution into four phases. Each phase pertained to a unique slope morphology based on assumptions regarding the catchment size of the gorge, associated channel width-to-depth relationships, and exhumation rates. Suggested exhumation rates of 0.28 mm/yr (Adams and Gabites 1985) becoming 0.6 mm/yr (Little et al. 1999) for last the 400 ka were applied by assuming congruent exhumation, whereby fluvial erosion (valley incision) was synchronous to uplift throughout Cromwell Gorge.

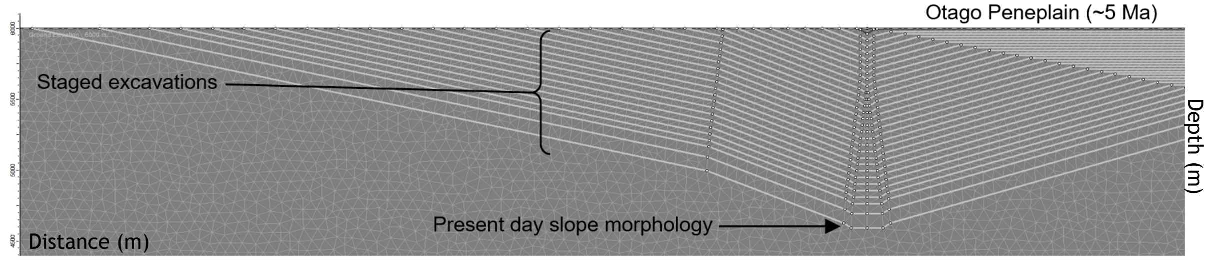

Figure 3. Sequential unloading (staged excavations) simulating valley evolution from Otago Peneplain to present day topography (1400 m deep).

In situ crustal stresses, including gravity and far field tectonic influences, were incorporated into sensitivity analyses using variable ratios (k) between horizontal (σ_h) and vertical (σ_v) stresses. Values for k ranged from 0.26 through to 5, representing purely gravitational stresses as a function of overburden weight and elastic deformation of the rock mass as well as topographical loading effects as suggested by Augustinus (1995) and Kinakin and Stead (2005).

Far field tectonic stresses associated with the obliquely convergent stress regime of the ongoing Kaikoura Orogeny were estimated from in situ field measurements carried out at Clyde Dam. In situ field stress measurements yielded maximum horizontal loads originating from the northwest (Table 1), coinciding with geodetic vectors associated with the Alpine Fault (Figure 4). FEM simulations of the topographic relief and rock mass properties at Clyde Dam produced induced gravitational stresses of similar magnitude to in situ minimum horizontal stresses. It was therefore deduced that the difference between the maximum and minimum in situ horizontal stresses corresponded to the far field tectonic stress regime, as indicated in Table 1. A locked in horizontal stress of 12.50-13.00 MPa were therefore incorporated into sensitivity analyses to represent active regional compressional tectonics.

Table 1. Locked in tectonic stresses derived from the difference between minimum and maximum in situ horizontal stresses (σ_h)

Analysis	In situ field stress results	FEM simulation results
Depth (m)	125.00	125.13
σ_v (MPa)	3.25	3.95
σ_h min. (MPa)	10.50	10.85
σ_h max. (MPa)	23.00	
σ_h max. (true bearing)	306^0 (similar direction as geodetic vectors indicated in Figure 4)	
Tectonic Stress (σ_h max. – σ_h min.)		12.50 – 13.00 MPa

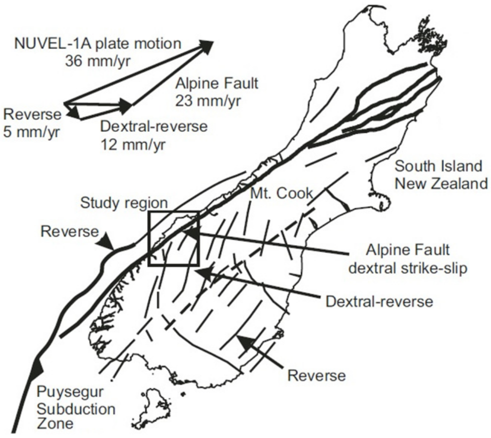

Figure 4. Geodetic measurement vectors for the NZ South Island, modified from Sutherland et. al. (2006) and DeMets et al. (1994).

4.4 Material properties

Mohr-Coulomb elasto-plastic rock strength parameters, derived during this study through a series of laboratory tests including Uniaxial Compression Strength (UCS), triaxial, indirect tensile, point load and direct shear box tests, were collated with existing literature pertaining to Otago schists. Selected parameters included in the FEM models are given in Table 2. Schistosity anisotropy was modelled by including an explicit joint network corresponding to foliation planes. Sensitivity variations included modelling the effects of i) anisotropy imposed by the intact filiations planes and ii) the effects of the lower shear strength subparallel foliation shear planes identified at an average spacing of 8 m throughout the Rakaia Terrane schist bedrock (related to extensional metamorphism). Geometric attributes (spacing and orientation) of foliation planes as well as Mohr-Coulomb properties were varied during sensitivity analyses. Foliation properties were modelled using both the intact rock strength and foliation shear planes, with a range of normal stiffness (k_n) between 438 to 5833 MPa/m, and shear stiffness (k_s) from 66 to 583 MPa/m.

Table 2. Peak and residual material properties derived for Cromwell Gorge Schists

	Poisson's ratio	Young's Modulus (MPa)		Tensile Strength (MPa)		Angle of friction (°)		Cohesion (MPa)	
		Peak	Res.	Peak	Res.	Peak	Res.	Peak	Res.
Greyschist	0.32[a]	3145[a]	2076[a]	0.005[a]	0	32[a]	28[a]	8.50[a]	0.12[a]
Greenschist	0.26[a]	6979[a]	4606[a]	0.005[a]	0	50[a]	27[b]	7.95[a]	0.26[b]
Foliation shears		-	-	0	0	27[a]	18.5[b]	0.12[a]	0.00[b]

[a] this study (2015-2016 data) [b] Smith and Salt (1991)

5 RESULTS

Sensitivity analyses reveal that specific combinations of high locked-in horizontal tectonic stresses, foliation stiffness and orientation contribute to the development of flexural toe buckling in the form of 'z-shaped' folds at the base of the Dunstan Mountain Range. Shear stress accumulates within a zone of abrupt maximum principal stress (σ_1) orientation change, which occurs between topographically induced gravitational stresses, where σ_1 is subparallel to the slope ('g' referenced stress trajectories in Figure 5), and far-field horizontal tectonic stresses, which dominate along the base of the slope ('t' referenced stress trajectories in Figure 5). Where moderately inclined foliations (30-40°) are orientated slightly steeper than the slope (23°), gravitationally induced σ_1 dominates the stress fields adjacent to the slope and acts subparallel to foliations, facilitating shearing along the preferential plane of weakness (foliations). Near the base of the slope, induced stress orientations are compounded by far field horizontal tectonic stresses, resulting in the abrupt rotation of σ_1 from subparallel to foliations to a sub horizontal orientation. This abrupt stress rotation reduces the magnitude of shear stress and subsequent displacement along foliation planes. High shear strains accumulate within this zone in the form of localised linear shear bands, which leads to the development of flexural 'z-shaped' folds resembling toe buckling (Figure 5). Deep-seated mass movements of the landslide complexes likely developed in response to toe breakout at the zone of maximum curvature along the 'z-shaped' flexural buckled folds and, were therefore influenced by the moderately inclined (30-40°) dip of the schist bedrock.

The anisotropic behaviour of schist is demonstrated using models with variable foliation orientations. Topographically induced gravitational stresses are obliquely oriented to sub horizontally to gently inclined (10-20°) and sub vertically (80°) inclined foliations. Maximum stress does not act directly parallel to the preferential plane of weakness represented by foliations, therefore, the magnitude of shear strain produced along foliation planes is reduced. Consequently, flexural 'z-shaped' folds do not develop, but deformation is expressed by flexural bending of the foliation planes as shown in Inserts A and B of Figure 5.

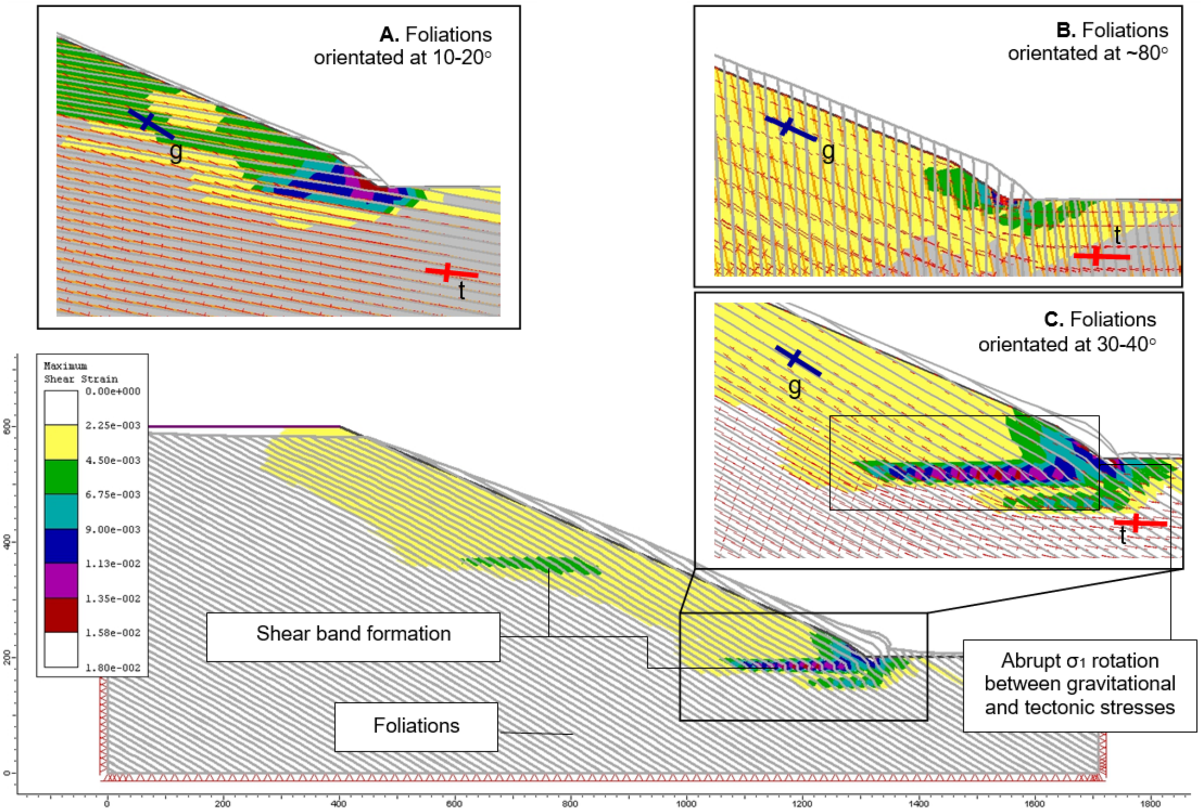

Figure 5. Foliations deform via flexural buckling developed along bands of maximum shear strain due to localised rotations of principal stress axes between induced gravitational (stress trajectories referenced g in insets) and far field tectonic principal stress (stress trajectories referenced t in insets) orientations. Note the height of the slope was scaled from 1400 m to 400 m for model simplification.

Development of flexural toe buckling is also influenced by stiffness of the material. A certain magnitude of competency is required to facilitate buckling. At low assigned shear and normal stiffness, the material yields along planar foliations because it has insufficient residual resistance and preferentially shears along existing planes of weakness (foliation shears). At higher stiffnesses, foliations facilitate plastic deformation withstanding complete dislocation, and deform in a curvilinear manner. The result of this behaviour is demonstrated beneath the slide base at Nine Mile Slide (Figure 2). Competency contrasts between stronger greenschist units deform through flexural buckling exhibiting oversteepened foliations, whereas the less competent pelitic greyschist completely shears without developing relative steepening along foliation planes.

6 CONCLUSION

Numerical FEM simulation of Cromwell Gorge's evolution from a relatively low relief surface corresponding to the Otago Peneplain to present day topography demonstrates that observed deformations at the base of the Dunstan flank of the gorge is a product of prolonged stresses acting on an anisotropic rock mass. Results indicate that a combination of induced gravitational stresses and high horizontal tectonic stresses coinciding with a lithologically variable rock mass are responsible for the anomalously oversteepened foliations beneath Nine Mile, No. 5 Creek and Dunlays Slides. Flexural toe buckling through shear and tensile dislocations of moderately inclined (30-40°) pervasively foliated schist bedrock develop in response to abrupt rotations of principal stress axes developed at the intersection of topographically induced slope parallel gravitational stresses and the far field horizontal tectonic stresses. Accumulation of strain in zones of localised rotation of principal stress axes initiate the development of flexural 'z-shaped' buckled folds at the toe of the slope. Progressive accumulation of strain along these buckled folds exceeded the low tensile and shear strength of the schist which led to toe break out and overall kinematic instability of the Dunstan flank of Cromwell Gorge.

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