Static failure mechanisms in sensitive volcanic soils in the Bay of Plenty Region, New Zealand

Philippa Mills[1,2] & Vicki Moon[1]
[1] School of Science, University of Waikato, New Zealand, pip.mills@outlook.co.nz, vicki.moon@waikato.ac.nz
[2] Coffey Geotechnics (Tetra Tech) NZ Ltd

Sensitive soils derived from volcanic material have contributed to major landslides in the Bay of Plenty (BOP) Region, New Zealand. Soil was sampled from sensitive material near the failure surface of a coastal landslide bordering Tauranga Harbour, New Zealand. Methods were adapted from Gylland *et al.* (2013a) including undrained, consolidated static triaxial tests at a high compression rate of 0.5 mm/min in order to replicate rapid loading during landsliding. At high effective confining pressures, our samples showed contractive p'-q' plots, strain softening stress-strain behavior coupled with rising pore pressures, and single or double shear band formation after peak strength was reached. This evidence indicates that like marine-derived sensitive soils from Norway (Gylland *et al.* 2013a,b), the low permeability of the clay allows pore pressure gradients to evolve, initiating collapse of clay microstructures into shear zones, where further excess pore pressure generation within the shear zone instigates progressive failure.

1 INTRODUCTION

It is well documented that sensitive soil failures in the BOP Region, New Zealand occur after significant periods of rainfall (Moon *et al.* 2015a,b). The failure mechanisms relating to rising pore pressures during heavy rainfall have not been studied for these soils. Fundamental strain softening failure properties are important to understand for accurate slope stability modelling (Gylland *et al.* 2013a,b; Thakur *et al.* 2014).

During undrained effective triaxial compression, sensitive soils derived from volcanic (Wyatt, 2009, Cunningham, 2012, Mills & Moon, 2016) and marine (Thakur *et al.* 2014, Gylland *et al.* 2013a) materials both show strain-softening, the reduction of shearing resistance following peak strength (Taylor 1937, Skempton 1964). Recently, strain softening in marine sensitive soils has been attributed to the generation of excess pore pressure in localised shear bands (Thakur *et al.* 2014, Gylland *et al.* 2013a,b). Strain softening is said to govern progressive failure, where failure in one soil element results in failure of a neighbouring soil element, like falling dominoes (Gylland *et al.* 2013b). This study aims to uncover whether volcanic sensitive soil in BOP, New Zealand exhibits similar failure mechanisms to marine- sensitive soils from Norway (Gylland *et al.* 2013a,b).

2 METHODS

Sensitive material was sampled from a bench dug 1.5 m into an outcrop at 23 m below ground surface, near the failure plane of a landslide at Omokoroa, Tauranga. Six samples were collected by vertical gentle tapping of stainless steel push tubes (d=48 mm, h=148 mm). Measurement of moisture content, wet and dry bulk densities, voids ratio, and Atterberg limits all followed ISO/TS 17892 standards (2014), undrained effective triaxial testing followed NZS4402 (1986), with the exception of the compression rate, where a higher rate of 0.5 mm/min was chosen over the testing time recommended, in accordance with Gylland *et al.* (2013a). B values greater than 95% were acheived during saturation. To determine brittleness or strain softening (SS) of the soil, we used Bishop's (1971) parameter:

$$\text{Strain softening (SS)} = (q_{max} - q_{residual}/q_{max})\times 100 \qquad (1)$$

where q_{max} and $q_{residual}$ are peak and residual deviator stresses respectively.

3 RESULTS

3.1 *Standard geomechanical properties*

The material was described as an extra-sensitive silty clay. Scanning Electron Microscope scans suggest the clay fraction to be halloysite dominated (Moon *et al.* 2015b). Porosity, void ratio, liquidity indices and moisture content are high, in keeping with previously published research on material derived from halloysite (Table 1) (Wesley 1977, Wesley 2009, Wyatt 2009, Cunningham 2012, Moon *et al.* 2015b). Many, saturated pores accounts for the low wet bulk density. Low activities (Table 1), are also in line with halloysite dominated sensitive material (Wesley 2009).

Table 1. Geomechanical properties of sampled material.

Parameter	*± S. Error*
Peak field vane strength (kPa)	66 ± 3
Remoulded field vane strength (kPa)	5 ± 1
Moisture content (%)	72 ± 1
Wet bulk density (kgm^3)	1320 ± 46
Void ratio (%)	2.3 ± 0
Sensitivity (%)	15 ± 3
Liquidity Index (%)	2.9

3.2 *Triaxial results*

Triaxial results for samples 1 – 6 (S1-6) are presented in Table 2. Figures 1a-b are characteristic responses for general failure behavior for all 6 tests. At greater effective confining pressure (ECP), peak deviator stress (q) and curvature of (q) peak increases. Post-peak rises in pore pressure (u) (Figure 1a) correlate with contractive, left trending effective stress path curves (p'q') along the CSL (critical state line) (Figure 1b), whereas post-peak drops in pore pressure correlate with p'q' curves that just touch the CSL, with some trending slightly to the right (Figure 1b). No significant relationship existed between strain softening and ECP (Table 2). All samples failed along either one sliding plane by shear, or as a wedge, where two sliding planes occur at roughly perpendicular angles.

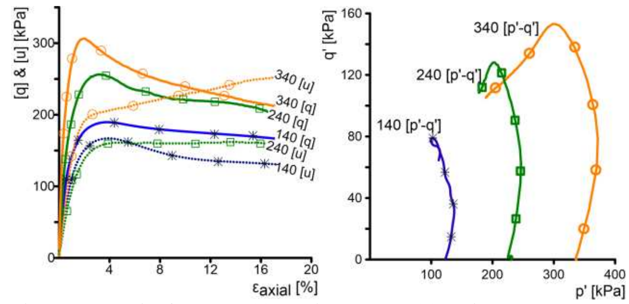

Figure 1. Results for S1-3: (a) Deviator stress (q) and pore pressure (u) (kPa) vs axial strain (ε) (%), and (b) p'- q' (kPa) stress path plots.

Table 2. Failure properties of the 6 triaxial tests (S1-6). ECP = effective confining pressure, B = pore water pressure coefficient, SR = strain rate, ε_f = axial strain at failure, q_f = deviator stress at failure, SS = strain softening (Bishop, 1971), FM = failure mode: W = wedge, S = shear.

Parameter	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*
ECP (kPa)	140	240	340	205	280	355
B	95	98	98	96	98	98
SR (mm/min)	0.5	0.5	0.5	0.5	0.5	0.5
ε_f (%)	1.9	3.2	2.0	3.1	3.4	3.5
q_f (kPa)	179	246	299	265	324	383
SS (%)	14	20	50	31	32	32
FM (%)	W	S	S-W	S	S	S-W

4 DISCUSSION

The contractive, strain softening responses observed in our volcanic soils concur with observations of undrained, consolidated tests on marine sensitive soils (Gylland *et al.* 2013a, Thakur *et al.* 2014). Low material permeability (Moon *et al.* 2015b) and high compression rate induce excess pore pressure gradients to evolve within the sample, leading to strain localisation, prior to or at peak stress (Gylland *et al.* 2013a), ending in progressive failure (Mills, 2017) within one or more shear zones. Thin section and micro-CT analysis on S1-S6 (Mills, 2017) evinced localised contraction within shear fractures, and progressive development of shear zones (Mills, 2017).

Shear zones likely create a preferential pathway for excess pore pressure to drain along, registering as a delayed response with the pore pressure base sensor (Fig.1a). Minor strain softening observed in S1 shows that some contraction occurred, but the drop in pore pressure after peak stress shows that the majority of the sample slightly dilated. This is because the lower confining pressures allowed pore pressure to dissipate within the sample, so no gradients could evolve to induce contractive failure in a shear band.

Recently, the horizontal strain or shear band displacement required to reach the residual state has been regarded as equally important to consider in the strain-softening equation (Quinn et al. 2011). Our experimental setup did not include horizontal displacement, therefore the brittleness parameter (SS) we used is an estimate of strain softening.

5 CONCLUSION

Failure mechanisms of volcanic sensitive soil sampled at a landslide location near Tauranga, BOP Region, New Zealand and marine sensitive soil from Norway (Gylland *et al.* 2013a, b) are compared. At high confining pressures, volcanic sensitive soils show strain softening, contractive responses, coupled with rising pore pressure post-peak deviator stress, and single or double shear band failure modes. Shear zone microstructure (Mills, 2017) and triaxial results show that volcanic sensitive soils fail in a similar manner to marine sensitive soils; excess pore pressure gradients initiate strain localisation, followed by contraction of clay microstructures and progressive failure in one or more shear bands.

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