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A methodology for examining soil-water characteristics of loess and loess-derived soils on Banks Peninsula, New Zealand.

K Yates
Department of Geological Sciences, University of Canterbury, NZ.
Kathering.yates@pg.canterbury.ac.nz (Corresponding author)

C Fenton
Department of Geological Sciences, University of Canterbury, NZ.
clark.fenton@canterbury.ac.nz

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ABSTRACT

Loess and loess-derived soils cover much of Canterbury, from the foothills of the Southern Alps to the Pacific Coast. These soils are of variable thickness, ranging from several metres up to 40m at the base of slopes on Banks Peninsula. In many areas primary, air-fall loess has been reworked by slope processes to form a loess colluvium. These soils are comprised predominantly of silt but can contain up to 45 % clay, giving rise to low plasticity clay behaviour. Loess and loess-derived soils are relatively dense, and can form vertical exposures. Dry densities are typically between 1.6 t/m3 and 1.8 t/m3, hence these soils do not display collapse behaviour common to other loess deposits around the World. Across Canterbury these soils display high dry strength but weaken rapidly with small increases in moisture content. Periodic wetting leads to a variety of slope failures related to internal erosion (tunnel gullying) and rapid loss of shear strength (debris flows and soil slides). In this paper, we present a methodology to investigate the effects of soil microstructure and soil suction on the shear strength and stability of loess soils in Akaroa Harbour.

1 INTRODUCTION

Loess and loess-derived soils, collectively termed loess deposits, greater than 1m thick cover approximately 10% of the South Island, New Zealand (Figure 1). Often considered a problematic soil, slope failures related to internal erosion and rapid loss of shear strength can occur within loess deposits. When dry, an in situ loess soil mass can stand vertically, and its strength and stability is often controlled by vertical discontinuities. However, upon small (2 – 3%) increases in moisture content, the shear strength of the soil matrix can weaken rapidly. The mechanics of this behaviour, in terms of the relative contributions of soil suction and inter-particle bonding to overall soil strength, is not well understood for loess deposits in Canterbury. Furthermore, the current understanding of the geotechnical shear strength of Canterbury loess deposits is based on a relatively small number of studies with limited geographic coverage.

As it is considered likely that the shear strength of the soil is controlled by a combination of the soil microstructure and negative pore pressures, understanding these mechanics is important for developing further understanding of the behaviour of loess slopes. This is the focus of current research which aims to inform future development in loess covered areas, and will improve the understanding of the behaviour of loess with respect to how changes in moisture content affect shear strength. The purpose of this paper is to outline the methodology of ongoing research by the University of Canterbury.

2 CANTERBURY LOESS DEPOSITS

Loess in Canterbury, New Zealand, is a yellowish brown windblown deposit with predominantly silt-sized grains. Sand content typically comprises fine, angular particles and, along with clay content, varies depending on location and degree of reworking. New Zealand loess has been formed from aeolian transportation and deposition of glacially derived rock flour. Deposition of these deposits has occurred primarily during the Late Pleistocene and Post Glacial (Holocene) (Bell et al., 1986; Bell and Trangmar, 1987; Bruce, 1973; Griffiths, 1973; Ives, 1973; Raeside, 1964; Sparrow, 1948). In Canterbury, the primary parent rock for loess is greywacke (Torlesse Group).

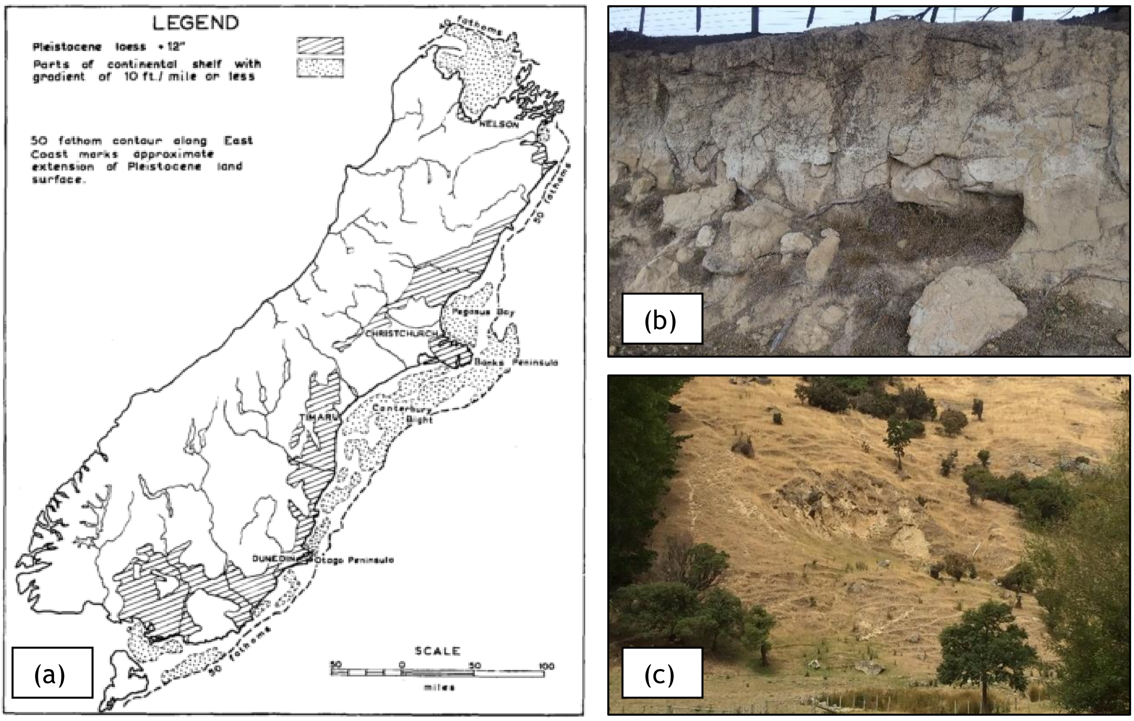

Figure 1: (a) distribution of loess >30cm thick in the south island (Raeside, 1964); (b) loess cutting with vertical discontinuities and large blocks released from the slope, Chorlton Rd, Okains Bay, Banks Peninsula; and (c) shallow slope instability in loess slope, Okains Bay

Loess greater than 1m thick covers approximately 10% of the South Island. The thickest deposits reach up to 40m thick, with the thickest deposits typically occurring at the base of slopes as colluvial aprons (Bell and Trangmar, 1987). Typically loess deposits overlie Pliocene age Cannington Gravels and Timaru Basalt in South Canterbury, and Miocene age volcanics in Banks Peninsula (Tonkin et al., 1974). Depending on location, loess deposits in Canterbury have been divided into 2 to 4 stratigraphic units separated by either colluvial layers or paleosols (Almond et al., 2007; Griffiths, 1973; Ives, 1973; Tonkin et al., 1974).

Two main groups of loess deposits are recognised in Canterbury: In situ (Primary air-fall) loess and loess colluvium. In situ loess refers to loess that has been formed from aeolian deposition, i.e., loess sensu stricto, and shows no evidence of reworking. In situ loess in Canterbury is predominantly quartzofelspathic silt, with minor amounts of accessory minerals and clay (generally illite and vermiculite) (Griffiths, 1973; Raeside, 1964).

Loess colluvium refers to materials that have been formed from the reworking of in situ loess by slope processes. It is also a quartzofelspathic silt or fine sand, but may also contain (volcanic) rock fragments (Bell and Trangmar, 1987). Loess colluvium generally has a lower bulk density, and greater permeability than in situ loess (Bell and Trangmar, 1987). Loess colluvium deposits are often discontinuous and variable in thickness, indicating episodic deposition (Bell and Trangmar, 1987).

When dry, the strength and stability of in situ loess is controlled by discontinuities in the soil mass. Cuttings within loess can stand vertically (Figure 2), however, the shear strength of the soil matrix can weaken rapidly upon small (2% - 3%) increases in moisture content (Hughes, 2002; Jowett, 1995; McDowell, 1989). This, and susceptibility to clay dispersion and erosion, can make loess subject to instability on slopes, particularly during and after intense rainfall events (Alley, 1966; Bell et al., 1986; Bell and Trangmar, 1987; Hutchinson, 1975). Wetting of the soil mass leads to a variety of slope failures related to internal erosion (tunnel gullying) and rapid loss of shear strength (debris flows and soil slides).

Our current understanding of the geotechnical characteristics of Canterbury loess deposits is based on a relatively small number of studies with limited geographic extent. In particular, the influence of soil microstructure and the relative contributions of soil suction and inter-particle bonding to overall soil strength are not well understood. As it is considered likely that the shear strength of the soil is controlled by a combination of both, examining the soil microstructure and the role of negative pore pressures in the loess deposits is the focus of ongoing research.

3 PROJECT OBJECTIVES

The primary purpose of this research is to examine soil suction and soil microstructure, and how they contribute to the shear strength and stability of loess and loess-derived soils in Canterbury, New Zealand. In particular:

1. How do loess slopes respond to rainfall in terms of pore water pressure, matric suction, water content and lateral deformation (if any), and what are the implications for slope performance and instability?
2. What is the impact of changes on pore water pressures on the shear strength of the loess?
3. What are the characteristics of the loess microstructure (including particle shape, angularity, particle size, clay bonding, location and consistency of clays within microstructure), and how does the application of moisture change this structure?
4. How does microstructure and soil suction contribute to the shear strength of loess?

Research will be conducted using a combination of field monitoring and laboratory testing techniques to allow both detailed observation of shear strength characteristics and global examination of these mechanisms in situ. The results of this research will inform future development in loess covered areas, and will improve the understanding of the behaviour of loess deposits with respect to changes in moisture content and shear strength.

4 FIELD INSTRUMENTATION

The field component of this research includes installation of subsurface sensors in a loess slope for a six month period over winter, spring and summer. Subsurface instrumentation will gather data on water content and soil suction during rainfall events. A similar approach has been used to investigate loess in China (Ng et al., 2003; Tsai and Wang, 2011; Xu et al., 2012, 2011; Zhou, 2012; Zhou et al., 2014). These data will allow analysis of the fundamental mechanics of rainfall-induced slope failures in loess in terms of its behaviour as a partially saturated soil.

4.1 Site Description

The field instrumentation will be installed in a grassed loess slope in Takamatua, Akaroa Harbour (Figure 2). The area to be instrumented is a north-facing 20° slope, approximately 90m in elevation. The site has been selected because it is isolated from stock and easily accessible for equipment installation. Preliminary subsurface investigations indicate that the site comprises approximately 1.5m of loess colluvium overlying primary in situ loess of an unknown thickness. No ground water was observed within the upper 2.5m of the loess profile. However the moisture content of the loess colluvium was slightly higher than the in situ loess (between 19 – 22% for the loess colluvium, and 19 – 20% for in situ loess). Shallow slope instabilities are observed near the site. Hummocky, uneven ground is located upslope, and downslope of the site several erosion features have been observed in road cuttings.

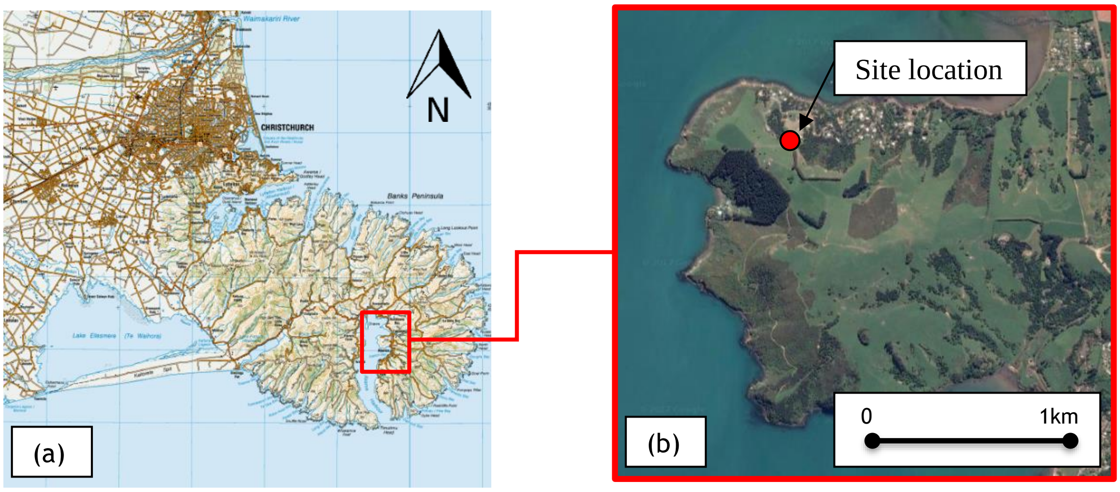

Figure 2: Site location for field instrumentation, (a) Topographic map of Banks Peninsula, (source: https://www.topomap.co.nz/ 1:250 000 Topographic map, accessed 6 March 2017) (b) Aerial image of Takamatua, (source: https://mapviewer.canterburymaps.govt.nz/ accessed 6 March 2017)

To enable the application of the results of the field monitoring to the surrounding Akaroa Harbour region, a detailed stratigraphy of loess in the area will be developed by mapping road cuttings at various sites. The purpose of this is to develop a regional geotechnical ground model incorporating lateral and stratigraphic variations in the loess soils geotechnical properties.

4.2 Instrumentation

The field instrumentation (Table 1) will be installed by hand auguring to the required installation depth. A ‘dummy’ frame will be pushed into moistened loess to form an indentation within the soil mass for the sensors to be installed. Once in the ground, the augur holes will be back filled. Back fill will be compacted to original field density to reduce the risk of preferential drainage.

Table 1: Sensors to be installed

Sensor type	Make	Quantity	Depths	Data collected
CS-616	Campbell Scientific	12	0.5m, 1.5m, 2.5m	Volumetric water content (%)
MPS-6	Decagon	12	0.5m, 1.5m, 2.5m	Soil suction (kPa)
Rain Gauge		1	Surface	Rainfall intensity (mm/min)

Data will be collected using a Campbell Scientific CR1000 data logger. Sensors will be installed in four arrays across the site (Figure 3). In each array there will be three CS-616 and three MPS-6 sensors. These sensors will be installed at three varying depths to capture progression of the wetting front during and after rainfall events. The data logger and rain gauge will be installed at the centre of the site.

Surface movement (if any) will be recorded by visual inspection and repeated real time kinematic GPS survey undertaken after each major rainfall event. Additional meteorological data, including temperature, sunshine hours, and barometric pressure near the site will be acquired from the NIWA database. Once the period of data collection has ceased, sensors will be removed by machine excavation. During this time samples will be obtained for laboratory testing. Further samples will be obtained from cuttings near the site for additional laboratory testing and Scanning Electron Microscopy (SEM) analysis.

Figure 3: Field monitoring site at Takamatua showing the location of the *in situ* instrument arrays. Site slopes towards the north.

Collectively, these data will allow comparison between the volumetric water content and the soil suction, and inform our understanding of the response of loess deposits to the infiltration of rain. Furthermore, these data can contribute to the soil water characteristic curve for the soil and present an in situ example of how rain infiltrates loess in the Akaroa Harbour area. Due to the known susceptibility of the loess in this area to moisture driven slope instability, it is important to gather such information to better understand the stability of slopes in these materials.

5 LABORATORY TESTING

Laboratory testing will be undertaken to examine the shear strength of the loess, and the relative contribution of microstructure and soil suction to the strength of the soil. The laboratory programme involves three components: investigation of index properties, triaxial testing, and the development of soil-water characteristic curves (Table 2). Undisturbed samples will be obtained by block sampling from existing exposures and from excavation at the instrumentation site in Takamatua.

Triaxial tests will be undertaken using a GDS motorised cell apparatus (Figure 4) to examine the soil strength behaviour in a laboratory setting. Testing will be undertaken at various moisture contents, including those recorded in situ at Takamatua. Correlation with soil suction during the tests will be obtained by the use of a soil water characteristic curve which will be developed during laboratory testing by means of the filter paper method and pressure plate test. This method allows the observation of soil suction in the absence of an unsaturated triaxial apparatus and direct measurement of soil suction during testing.

Figure 4: GDS triaxial cell

Triaxial testing will be undertaken on both undisturbed and remoulded *in situ* loess and loess colluvium to examine the influence of soil microstructure on the shear strength. In addition, pre- and post-failure samples will examined by Scanning Electron Microscopy (SEM) to investigate the role of inter-particle bonding during shearing. To examine the anisotropy of the soil mass, two orientations of *in situ* loess samples will tested using the triaxial apparatus. These orientations include sample alignment so that principle stress is normal to grain arrangement, and alignment so the principle stress is 45° to grain arrangement.

Table 2: Laboratory testing schedule

Category	Test	Purpose
Geotechnical index testing	Atterberg Limits	Examine relationship between particle size grading, clay mineralisation and plasticity of loess
	Particle size distribution and clay content (hydrometer method)	
	Clay mineralogy (XRD testing)	
	Moisture content (at start and end of field trials)	Examine change in gravimetric water content throughout field trials
	Dry density	Inform relationships between density and other geotechnical characteristics
	Specific Gravity	Characterisation & calculate initial void ratio
	Oedometer Test (stress history)	Examine consolidation state and infer impacts of stress state on soil consolidation Examine the possibility of collapse failure in loess
Soil water characteristics	Soil-water characteristic curve test (SWCC)	Determine the soil-water characteristic curve for both drying and wetting of the loess.
Triaxial testing on *in situ* and remoulded loess	Isotropically Consolidated drained test (ICD) and Isotropically Consolidated undrained test (ICU) (Monotonic loading)	Examine stress-strain relationship, volumetric change, dilatancy, pore water pressure, critical state line and stress paths for loess
	Anisotropically Consolidated drained test (ACD) and Anisotropically Consolidated undrained test (ACU)	Examine the influence of slope effects on the shear strength of loess

Category	Test	Purpose
	(Monotonic loading)	
	Constant deviator stress test (CQS)	Simulate the stress paths of saturated soil in a loess slope with a rise in groundwater level. Keep deviator stress constant but increase pwp.

6 PROJECT OUTPUTS

The primary purpose and output for this research is to develop a better understanding of soil-water characteristics of loess and loess-derived soils in Canterbury, New Zealand. This is achieved by examining the interaction between soil suction and volumetric water content in both a field and laboratory setting. By correlating field measurements with laboratory shear strength testing we can better understand how loess slopes respond to rainfall and the implication of this to slope performance and instability.

The outputs of this research include:

- Field observations on the behaviour of a loess slope in terms of soil suction and volumetric water content, subject to seasonal rainfall.
- Shear strength data from a range of moisture contents.
- Microscopic imaging of the soil microstructure of loess.
- Definition of the soil water characteristic curve for loess in Canterbury.

Because the current understanding of the soil microstructure of loess at this time is limited, SEM imaging will inform our understanding of the soil matrix characteristics (including particle shape, angularity, particle size, clay bonding, location and consistency of clays within microstructure). Using these data, we will be able to develop a better understanding of the performance of loess slopes for engineering design of cut slopes, foundations, and management of slope failures. Furthermore, this information will be able to inform land development and assessment of the slope failure susceptibility.

7 CONCLUSIONS

Loess deposits are widespread in Canterbury, New Zealand. Due to the susceptibility of loess slopes to failure during rainfall events, the relationship between shear strength and moisture content is important to understand. As a consequence, a proposed methodology for researching this has been outlined in this paper. By examining the interaction between soil suction and volumetric water content in both a field and laboratory setting, the shear strength of loess can be better understood. Data gathered during subsurface field instrumentation in Banks Peninsula will inform on how loess slopes respond to rainfall, and inform on the implication of this to slope performance and instability.

8 ACKNOWLEDGMENTS

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