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***Laboratory simulations of a slow-moving landslide
mechanisms***

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TECHNICAL SUMMARY

Slow-moving landslides are a significant hazard in New Zealand and globally and better characterisation of their potential movement mechanisms during earthquake and rainstorm is needed. Understanding their behaviour requires a combination of high-resolution field monitoring, well-constrained ground models and laboratory testing that accurately replicates the natural stress conditions, but this combination is rarely available.

In our study we used a dynamic back-pressured shear box to simulate representative stress conditions in the slow-moving Utiku Landslide during phases of pore-water pressure fluctuation and dynamic shear. We combine this novel dataset with monitoring records and numerical modelling from Utiku landslide to provide new insight into its movement mechanisms.

Our laboratory results show that during periods of elevated pore-water pressure, displacement rates were influenced by two components: 1) an absolute stress state component (normal effective stress); and 2) a transient stress state component (the rate of change of normal effective stress). The behaviour observed in the laboratory was consistent with the ground-monitoring records and explains why the relationship between displacement rate and pore-water pressure is different during periods of acceleration and deceleration in some slow-moving landslides.

During dynamic shear experiments we showed that displacement rates were controlled by the extent to which the forces operating at the shear surface were out of balance. Once these forces exceeded the yield acceleration, displacement rates increased rapidly with distance normal to the failure envelope in plots of shear stress against normal effective stress. By combining laboratory and numerical simulation data we demonstrated that, during strong earthquake accelerations, strain should increase rapidly with relatively minor increases in the out of balance forces (reducing the K_v / K_{max} ratio). Therefore, we reasoned that large landslide displacements could occur when accelerated by strong earthquakes, but such accelerations in the study area occur infrequently. Thus, in this area over long timescales (i.e. multiple seismic cycles) landslide displacement will be predominantly controlled by pore-water pressures.

By combining the specialised laboratory testing with field monitoring, well-constrained ground models, and numerical simulations, we showed how the mechanisms of deformation occurring along a landslide shear surface could control the movement patterns seen in many large, slow moving translational landslides. The combining of these approaches provides a robust framework to use in the hazard assessment of landslides that could be mobilised by both strong earthquakes and significant rainfall.

1. INTRODUCTION

Understanding how slow-moving landslides accelerate and decelerate and under what circumstances they may catastrophically reactivate are important for hazard management and implementing landslide mitigation strategies. Several studies have successfully demonstrated that landslide movement is dependent upon mechanisms of deformation occurring on the landslide shear surface (Petley et al. 2005a; 2005b; Ng & Petley, 2009; Carey & Petley, 2014). At the same time there have been significant advances in landslide monitoring techniques to determine the causes of landslide movement in pre-existing landslides and the development of warning systems. Despite these advances, very few studies have considered how pore-water pressure changes and earthquake shaking influence slow-moving landslide displacement rates at the same high spatial and temporal resolution. At which Field monitoring data and laboratory testing that accurately replicates the complex stress conditions within slopes are required, the combination of which is rarely available. This research provides an example where this has been done.

In New Zealand, slow-moving landslides are common in soft sedimentary rocks. These sedimentary rocks are usually of Neogene age, fine grained sandstones and mudstones. They cover approximately 17% of New Zealand's land surface (Fig 1 a) (Massey et al. 2016). The New Zealand Landslide Database contains approximately 7,000 landslides within these sediments (Fig 1 b). (Dellow et al. 2005; Rosser et al. 2017), the majority of which are relatively slow-moving, deep-seated, translational slides that reactivate frequently (Massey, 2010). Very few of these landslides have been subject to long-term monitoring and the mechanisms through which they accelerate and decelerate are poorly understood.

The Utiku landslide complex (Fig. 1 a) is the one of the landslides in these materials that has been the subject of detailed study. Surface movement monitoring has been undertaken at the site since 1965, and high-resolution monitoring data collected since 2008. The landslide is classified as a reactivated deep-seated translational landslide with a volume of about $22 \times 10^6 \text{ m}^3$ (Massey et al. 2013) The long monitoring records reveal that the landslide generally moves slowly to very slowly and has repeatedly damaged both the North Island Main Trunk railway (NIMT) and State Highway 1 (SH1), which cross the landslide (Fig. 1 b).

The Utiku landslide has been intensively studied using detailed field mapping, borehole analysis, evaluation of historical movements and the analysis of data from piezometers, inclinometers and rain gauges (Massey, 2010). The displacement time series reveals displacement behaviour (Massey et al., 2013) where most of the movement occurs during periods of comparatively rapid movement, of up to 120 mm of displacement per event at rates of up to 21 mm/day. Movement usually coincides with seasonal peaks in pore-water pressure, with movement primarily associated with basal sliding. Massey et al. (2013) showed that while movement initiates with increases in pore-water pressure, the cessation of movement is poorly correlated with pore pressure or any other monitored factor.

Over the same monitoring periods no episodes of landslide movement could be attributed to earthquake shaking, even though earthquake ground accelerations were recorded during the observation period, of which the largest (1.0 m/s/s, or 0.1 g) had a >20-year return period (Massey et al. 2016). Consequently, Massey et al (2016) used the mean relationship between the yield acceleration (KY) and the maximum average acceleration of the landslide mass (Kmax), to determine the likely range of displacements of the Utiku landslide at given levels of peak free-field horizontal ground acceleration (AFF). They conclude that the modelled mean earthquake induced landslide displacement rate is about 0.005–0.05 m/year suggesting that earthquake-induced displacements are not the driver of the long-term movement rate of this landslide, and by implication other similar landslides with low-angle basal slide surfaces, formed in similar materials, in the area. However, Massey et al. (2016) point out that their results do not mean that earthquake-induced displacements of the landslide have not occurred at Utiku, or that the amount of landslide displacement during a large earthquake is small.

In this study we conducted a suite of laboratory experiments that simulate a range of pore-water pressure and dynamic stress scenarios on samples, with typical Neogene mudstone properties, collected from the Utiku landslide complex, Manawatu-Wanganui, New Zealand. We compared the displacement patterns we observed in the laboratory to high-resolution monitoring records collected from the landslide between

2008 and 2017, and numerical modelling of potential ground displacement during earthquakes, to get insights into the processes controlling the complex movement patterns observed at this location.

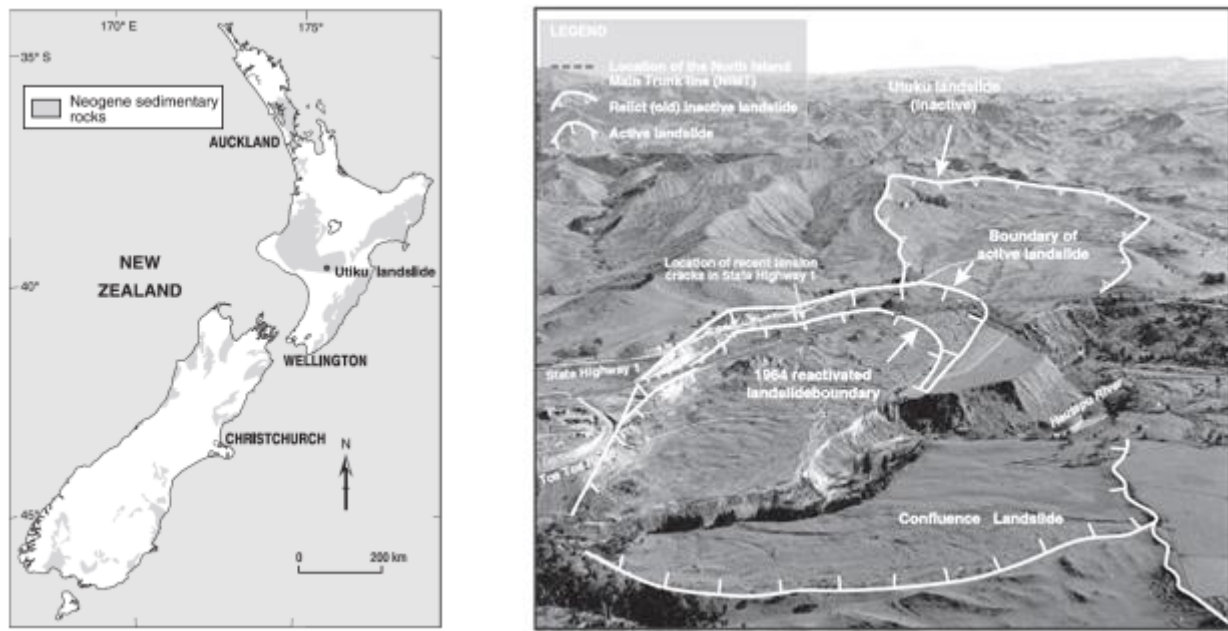


Figure 1. (a) The Utiku Landslide location in Neogene sedimentary rocks of North Island, New Zealand and (b) the landslide complex in relation to the State Highway and Main Trunk Line Railway (after Massey et al. 2013).

2. OBJECTIVES & METHODS

Our study had three main objectives:

1. Undertake a series of specialist laboratory tests to replicate linear and stepped patterns of pore-water pressure increase and decrease on the shear plane under imposed constant normal and horizontal stresses.
2. Undertake a series of specialist laboratory tests to replicating different magnitudes and frequencies of simplified earthquake shaking by varying the dynamic shear stresses on the shear plane.
3. Compare our experimental data with the monitoring records and modelling results available for the landslide to contribute new knowledge regarding the causes of and potential for future landslide movement.

Our laboratory experiments were conducted in a Dynamic Back-Pressured Shear Box (DBPSB) (Fig 2). The DBPSB is highly modified direct shear device, constructed by GDS Instruments Ltd and described in detail by Brain et al. (2015) and Carey et al. (2017). The apparatus can function as both a conventional direct shear and back-pressured shear machine and provides both static and dynamic control of: horizontal (shear) and axial (normal) force and displacement; total stress; and effective stress. In addition, sample pore-water pressure can be monitored throughout each experiment.

Samples were fully saturated to simulate the shear-zone conditions within the landslide complex during periods of movement using the methodology previously described by Carey et al. (2016). Each sample tested was then subject to a normal effective and shear stress to represent an initial stable slope condition.

To explore the displacement response of the landslide shear surface to increasing and decreasing pore-water pressures we subjected samples to different patterns pore-water pressure change (linear and stepped) at constant total normal and shear stresses and measured their displacement response. To replicate different earthquake loading a series of dynamic, shear stress-controlled experiments were conducted. During each dynamic experiment a different maximum shear stress was applied to the sample and the horizontal (shear) displacement and pore-water pressure response of the sample was measured.

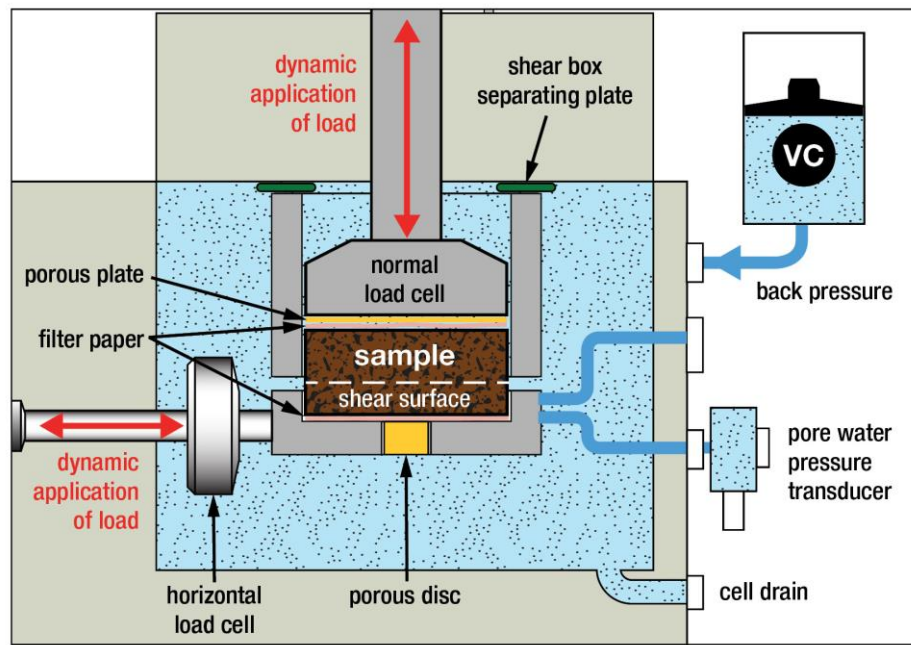


Figure 2. Schematic diagram of the DBPSB apparatus.

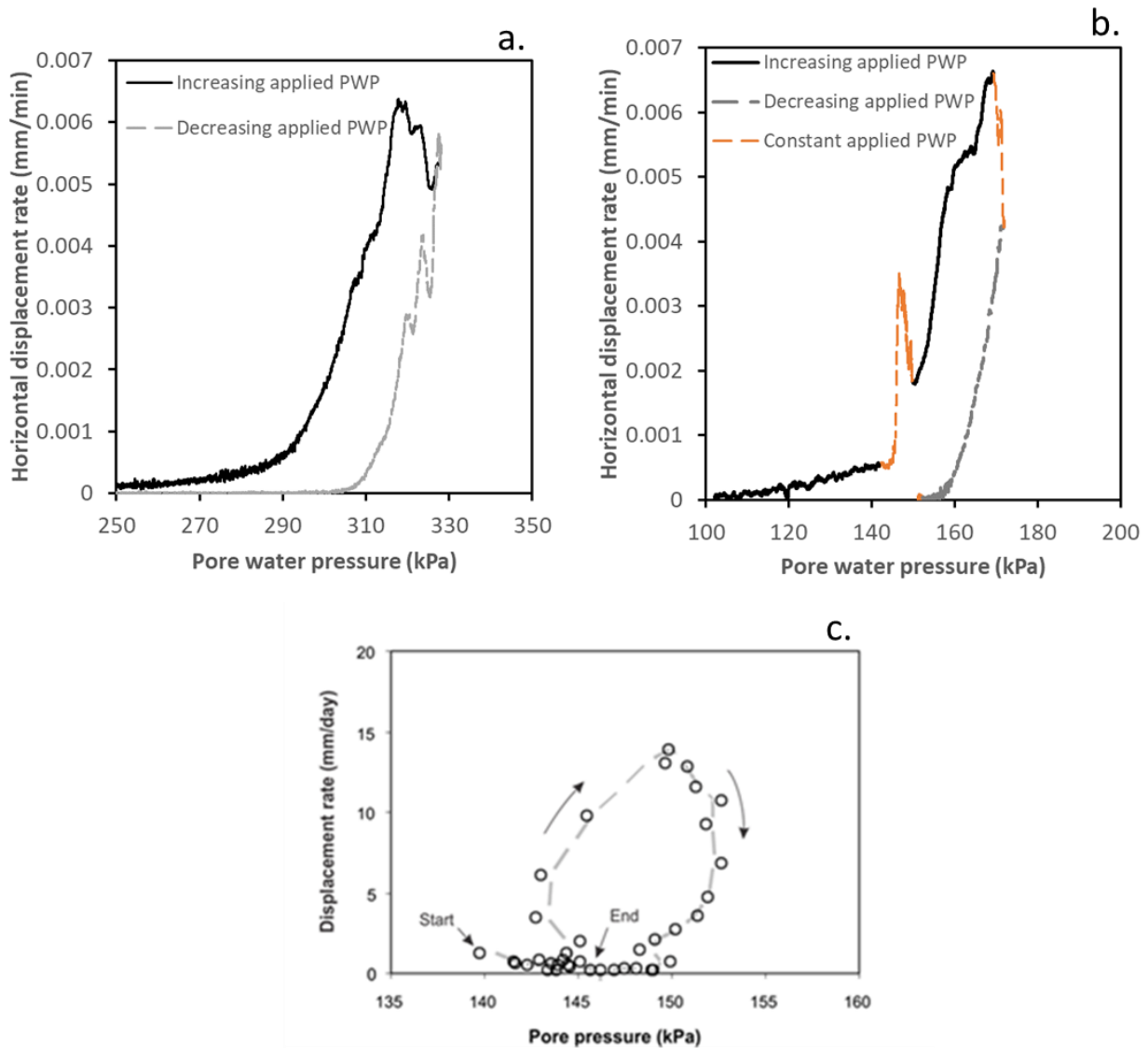


Figure 3. Relationship between displacement rate and pore-water pressure during periods of acceleration and deceleration (a) Horizontal displacement rate against pore-water pressure during a linear increase in and decrease applied porewater pressure (applied 5 kPa/hr). (b) Horizontal displacement rate against pore-water pressure during stepped increases and decreases in pore-water pressure. (c) Displacement rate against porewater measured in the Utiku landslide complex during periods of accelerated ground movement (from Massey, 2010).

3. SUMMARY RESULTS

Our experiments successfully simulated the non-linear relationship between displacement rate and pore-water pressure during period of acceleration and deceleration measured within the landslide during periods of acceleration displacement (Fig 3) (Massey et al. 2013). In addition, experiments applying stepped increases in pore-water pressure demonstrated that the relationship between pore-water pressure and displacement rate is complex and appears to be a function of both the absolute pore-water pressure (i.e. the absolute mean effective stress) at the landslide shear surface and the rate of change of pore-water pressure (i.e. the rate of change of normal effective stress) (Fig 3). The style of behaviour is consistent with observations from previous laboratory based studies (Ng and Petley, 2009; Petley et al. 2017) and may also explain the movement patterns observed in other slow-moving landslides, such as 'stick-slip' behaviour (e.g. Allison and Brunsden, 1990).

During our dynamic experiments where the applied maximum shear stress exceeded the conventional failure envelope we observed permanent displacement at a constant displacement rate per cycle (Fig 4a and b) which increased with degree by which the failure envelope was exceeded. We used the method adopted by Brain et al. (2015) we plotted the displacement rate per cycle against the distance normal to the conventional failure envelope (Figure 4c) to show that displacement rates increase exponentially.

While large shear stresses will generate high excess pore-water pressures within the landslide, our results suggest that these materials are not susceptible to liquefaction. Instead dynamic shear stresses, that exceed the conventional failure envelope of the sample generate out of balance forces that trigger permeant displacement. The magnitude of displacement that occurs is therefore a function of the magnitude and duration of the force imbalance. We infer from this that the frictional properties of the materials we tested do not increase (strain harden) or decrease (strain weaken) but remain constant during dynamic shaking. We anticipate, therefore that the relationship between displacement rate and normal distance from the failure envelope would also be observed for complex seismic wave forms, but this requires further investigation.

We compared our results to numerical simulations from Massey et al. (2016) by deriving strain for different K_v / K_{max} ratios from our laboratory data (Fig 5). Both data sets can be described by power law functions indicating strain increases rapidly with decreasing K_v / K_{max} ratios, indicating that the tested material and the simulated landslide strains are both controlled by the amplitude of earthquake acceleration above the yield acceleration.

The movement rates measured during dynamic shear tests were several orders of magnitude greater than would be anticipated by similar magnitudes of normal effective stress reduction during periods of elevated pore-water pressure. However, Massey et al. (2016), show that the annual frequency of such large earthquake accelerations in the Utiku area, as defined by the National Seismic Hazard Model (NSHM) (Stirling et al. 2012), are low. For example, an earthquake free-field Peak Ground Acceleration (PGA) of 0.5 g (4.9 m/s/s) has an annual frequency of occurrence of 6.5×10^{-4} (a return period of 1,536 years). Such an earthquake is forecast to induce a permeant displacement in the order of 10 m (Massey et al., 2016), indicating that such large displacements are unlikely to occur frequently. Massey et al. (2016) conclude that the estimated mean landslide displacement rates from earthquake modelling are below those induced by seasonal increases in pore-water pressures, and that increases in pore-water pressure account for most of the recorded landslide displacement as they occur more frequently than strong earthquakes.

We concluded therefore that our novel laboratory experiments are capable of simulating representative stress conditions in a slow-moving landslide during phases of pore-water pressure fluctuation and earthquake shaking. Combining our experimental approach with high precision monitoring and well-constrained numerical simulations shows how the mechanisms of deformation occurring along a landslide shear surface may control the movement patterns of many large, slow moving translational landslides.

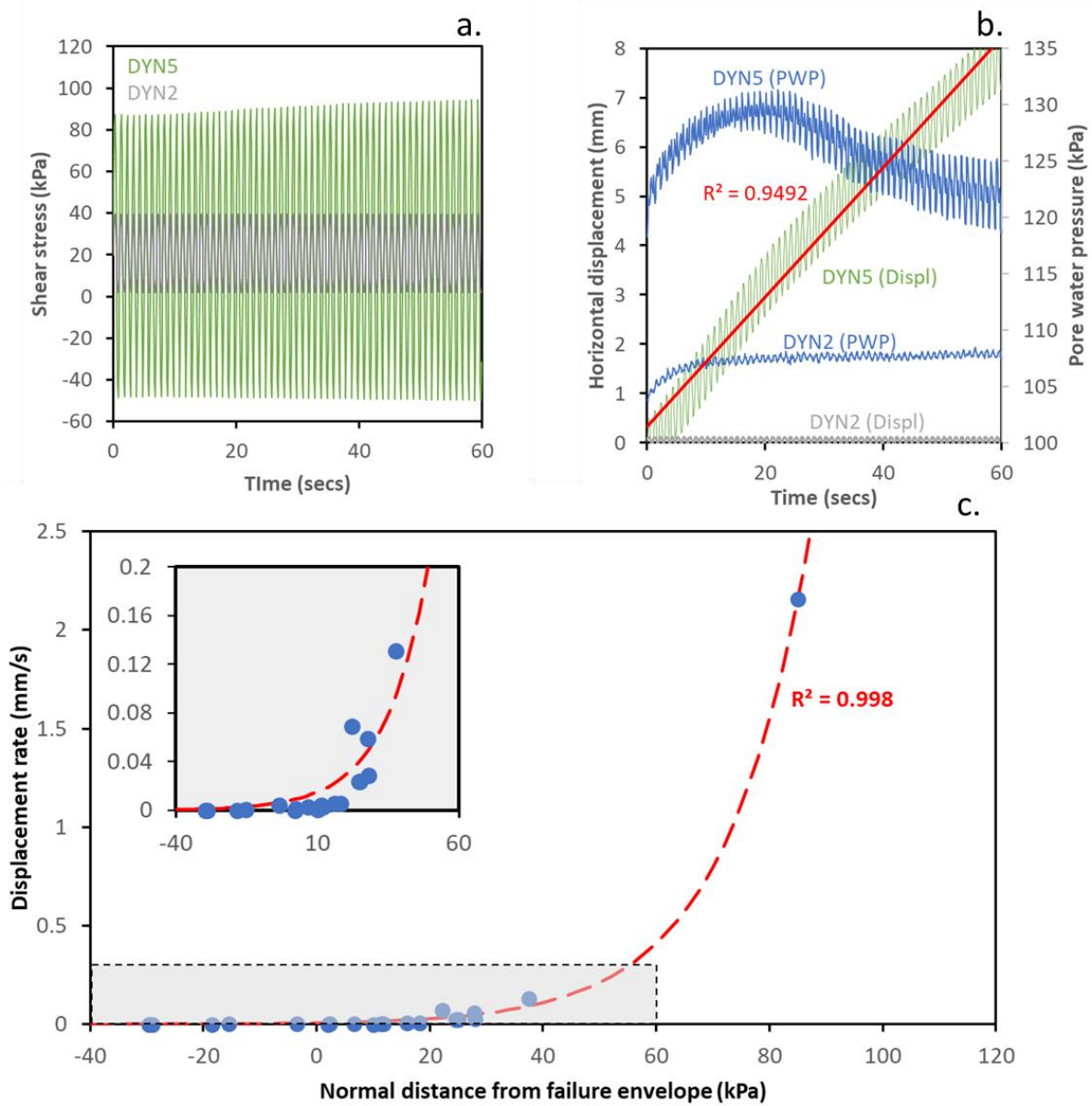


Figure 4. Results from the dynamic shear experiments (a) Dynamic shear stress cycles applied at 2 Hz experiment DYN5 and DYN2 (b) Displacement and pore-water pressure response measured during experiments DYN5 and DYN2 (c) Displacement rate against normal distance from the failure envelope for dynamic experiments undertaken at 2 Hz and 1 Hz.

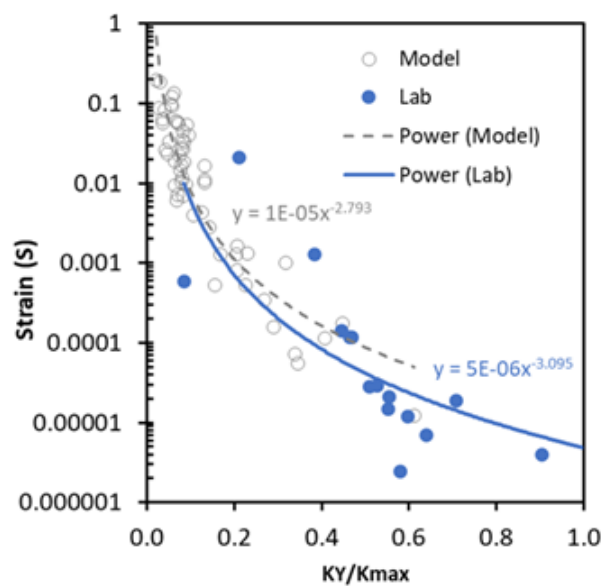


Figure 5. Strain versus K_y/K_{max} ratios from numerical simulations after Massey et al., (2016) (hollow circles) and laboratory experiments (solid circles), in response to a given dynamic load.

5. FUTURE WORK

Our study provides a novel approach to assess potential displacement responses of active landslide complexes during earthquakes and rainstorms. Similar research is needed to better understand active landslide in areas of different geology vulnerable to large earthquakes and large rainfall events. Such studies require a combination of long-term monitoring, ground model construction and laboratory testing.

The study also shows how the deformation properties of landslide shear zones materials are a fundamental control on landslide displacement potential and further research is greatly needed to understand the deformation properties of other materials which are known to be prone to instability in New Zealand (e.g., sensitive volcanic soils, schists).

Our research is of direct relevance to the reactivation potential of landslides that occurred during the 2016 Kaikoura earthquake and we intend to use the knowledge we have developed here to inform ongoing projects (e.g., Earthquake Induced Landscape Dynamics Endeavour programme, SLIDE).

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