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Patterns of movement in reactivated landslides

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ABSTRACT

The primary aim of this research was to study the relationship between landslide motion and its causes, with reference to large, slow moving, reactivated translational rock slides. Surface displacements of the 22×10^6 m^3 Utiku landslide, in central North Island, New Zealand were measured using continuous GPS (cGPS), for three years. The nature of the movement of such slides has often been difficult to determine because of poor temporal and spatial monitoring resolutions. After removal of tectonic plate motion, the temporal pattern of the landslide's surface motion could be understood to arise from irregular episodes of faster (up-to-21 mm/day) and slower (up to 26 mm/yr) post-failure landslide displacement, and seasonal cyclic displacements of about 20 mm/yr–10 mm per half year in alternating directions. Intervals of faster motion gave rise to displacements of between 10 and 120 mm per event. Faster displacement was associated mostly with basal sliding (mechanism 1), involving deformation within a thin clay seam as recorded by borehole inclinometer surveys. Slower surface displacement involved permanent internal deformation of the larger landslide mass, consisting of plastic deformation within the landslide body and/or slip along existing internal planes of weakness, and slip on the slide base (mechanism 2); it accounted for up to 26 mm/yr of displacement at a mean angle of about 49° from the horizontal, indicating that the slide mass was thinning as it moved down slope. Seasonal cyclic displacements were synchronous with changes in pore pressure, suggesting that it is a shrink/swell process (mechanism 3) associated with wetting and recharge of groundwater during the wetter winter months, leading to a downslope movement, and soil shrinkage leading to upslope rebounds during the dryer summer months. The brief periods of faster displacement were triggered by seasonal peaks in pore pressure, linked to long periods (12 to 20 weeks) of increased precipitation and lowered evapotranspiration. Faster displacement, however, was not arrested by lowering pore pressure or by any other monitored factor. Similarly, periods of slower displacement did not correlate with pore pressure changes, or with any other monitored factor. This study has shown that the annual movement pattern of a reactivated landslide is a combination of these processes that generate a complex overall movement record. The field measurements showed real variability arising from variations in rainfall and pore pressure, which were overprinted with measurement noise that may mask some other processes.

1. Introduction

The movement of reactivated landslides can impose a large financial cost on society. Lee and Jones (2004) and Mansour et al. (2011) note that whilst reactivated landslides generally do not kill many people, they are responsible for high levels of economic loss. For example, the 1956–1969 Portuguese Bend Landslide in California (which caused no fatalities) resulted in losses and court-imposed damages of US$86 million ($680 million equivalent value in 2013). In many parts of the world, unexpected reactivation of landslides generates the highest levels of non-coastal landslide hazard (Lee and Jones, 2004). Understanding the behaviour of reactivated landslides is therefore important, but at present detailed knowledge of these processes is surprisingly scant, primarily because the datasets that can be used for such analyses have been difficult to collect.

A range of techniques have become available in recent years that allow monitoring of patterns of landslide movement with improved temporal and spatial resolutions. Application of these techniques, which include laser-based geodetic techniques, differential GPS, and ground- and satellite-based radar, when combined with monitoring of potential causal and triggering factors, is providing new insights into the mechanisms of slope deformation (Thiebes, 2012). In turn, this permits improved slope management, and is paving the way for better forecasting and prediction of likely landslide behaviour (Petley, 2010; Thiebes, 2012).

In order to link landslide-causal factors to their consequences, in this case movement patterns, high-precision measurement of the movement of reactivated landslides over a representative time period (several years rather than days or months) is required, coupled with analyses of the resulting datasets. Whilst some studies address this issue (e.g., Corominas et al., 2005; Petley et al., 2005; Van Asch et al., 2007 and

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Thiebes, 2012), the development of approaches for such analyses is in general lagging behind the advances in the ability to measure and create the datasets. It is only through detailed analyses of a wide range of landslide types in diverse materials that general principles of movement will be understood.

For specific landslides under study, Corominas et al. (2005), Gonzalez et al. (2008), and Matsuura et al. (2008), found that velocity increased non-linearly as pore pressure increased. In addition, Bertini et al. (1984) and Gonzalez et al. (2008) showed that for the same value of pore pressure, the velocity when groundwater was rising was higher than during lowering (Picarelli, 2007), implying that the relationship between shear stress and normal stress, as assumed by the Mohr–Coulomb failure criterion may in some cases be non-linear. The relationship between pore pressure (groundwater) and landslide movement can be complicated by complex landslide geology and hydrogeology, in particular by the contrasting permeability of intact, fissured and sheared materials forming the slide mass, the occurrence of multiple slip surfaces within the slide mass leading to a complex displacement profile with depth, and the presence of large-scale heterogeneities providing direct conduits for surface water into the landslide (e.g., Corominas et al., 1999; Van Asch et al., 2007, 2009). Consequently, large, slow slides often show an erratic and complex response to hydrological input (Corominas et al., 2005; Malet et al., 2005; Van Genuchten and De Rijke, 1988; Van Asch et al., 2007, 2009).

It has been hypothesised that landslide velocity, although clearly linked to pore pressure-induced changes in effective stress, is also governed by rate-induced changes in shear strength of the materials, caused by behaviour of the clay particles during shearing (Lupini et al., 1981; Skempton, 1985; Angeli et al., 1996; Picarelli, 2007); and/or consolidation and strength regain during periods of rest (Nieuwenhuis, 1991; Angeli et al., 2004). It has also been proposed that shear-strength parameters, represented as c' and ϕ' in the Mohr–Coulomb failure criterion, can be modified by inclusion of a viscous resistance component (Bertini et al., 1984; Leroueil et al., 1996; Corominas et al., 2005; Van Asch et al., 2007, 2009; Picarelli, 2007; Gonzalez et al., 2008). Many authors have used viscosity functions to better describe and in some cases predict the motion patterns of these types of landslide assuming that once motion is triggered, the landslides move by visco-plastic flow, rather than by rigid-plastic frictional slip, (e.g., Iverson, 1985; Angeli et al., 1996; Corominas et al., 2005; Van Asch et al., 2009; Ranalli et al., 2009).

This paper proposes a framework for understanding the movements in reactivated landslides, based upon a high-quality dataset from one such landslide, located at Utiku in the North Island of New Zealand (Figure 1). The Utiku landslide is a large, reactivated, deep-seated, translational landslide that displays comparatively low rates of movement. Nonetheless, the landslide movement has repeatedly damaged both a major highway and an important railway that traverse the landslide. This study reports on three years of high-resolution monitoring, and explores relationships between the patterns of movement and their controlling factors. Even though the geometry of the landslide is comparatively simple, and the materials controlling failure are not complex, the observed patterns of movement are not straightforward. Novel techniques for movement analysis allow the underlying patterns to be determined. Based upon this analysis, a framework through which the movement of reactivated landslides can be understood is proposed.

1.1. The Utiku landslide

The Utiku landslide is located at 39.75°S, 175.83°E in the central part of North Island, New Zealand (Figure 1). The climate is temperate oceanic in the Köppen–Geiger classification, and characterised by warm summers (December through to February) where the average daily temperature is 22 °C, and cooler winters (June to August), where the average daily temperature is 11 °C. Rainfall does not vary significantly between winter (mean monthly rainfall 70 mm), and summer (mean monthly rainfall 81 mm), with a mean annual rainfall of about 960 mm.

Fig. 1. The location of the Utiku landslide in New Zealand, and the extent of exposed Neogene-age sedimentary rocks.

The landslide volume is about 22×10^6 m^3, and it can be classified as a reactivated, deep-seated, translational landslide in the Cruden and Varnes (1996) scheme. Prior to this study, the landslide had been monitored at a low temporal resolution since 1965; measurements during this period indicate that it moved extremely slowly to very slowly (16 mm/yr < x < 1.6 m/yr) (Stout, 1977). Nonetheless, both the North Island Main Trunk railway line (NIMT) and State Highway 1 (SH1), which cross the landslide, have been repeatedly damaged by movements, although they remain in use (Figure 2).

Although the Utiku landslide is interesting in itself, its observed patterns of movement broadly illustrate the behaviour of large translational mass movements in weakly consolidated Neogene materials, primarily silty, fine sandstones and sandy siltstones of marine origin, in New Zealand and other sites of similar materials around the world. In New Zealand there are over 7000 mapped landslides each with a plan area of >10,000 m^2 in these materials. Some of these are shown in Fig. 3. The majority of these are slow-moving, relatively deep-seated, translational landslides (Dellow et al., 2005; Massey, 2010). The large number of landslides in these Neogene deposits results from a combination of factors, including the low intact strength of the slide mass (typical unconfined compressive strengths are in the order of <1 to 20 MPa (Read and Miller, 1990)); deeply incised rivers; extensive tectonic folding, and faulting; bedding-plane defects (bedding-plane shears); and regionally persistent, bedding-parallel clay seams along which sliding may occur (Stout, 1977; Thompson, 1982; Mountjoy and Pettinga, 2006; Reyes, 2007).

The regional tectonic setting of the Utiku landslide is one of gentle folding from east–west compression (Lee et al., 2012). Associated