Understanding patterns of movement for slow moving landslides

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ABSTRACT

The movement of many landslides is controlled by the force imbalance associated with a reduction in shear resistance caused by a decrease in normal effective stress as pore water pressures increase. This basic premise might lead to an assumption that the movement rate has a simple relationship with the pore water pressure / normal stress state, but previously studies have shown marked differences in this relationship according to whether pore water pressures are rising or falling. This paper reviews examples from the literature in which high resolution monitoring allows the relationship between the movement rate and the pore water pressure / normal effective stress state to be determined. We show that a variety of relationships exist between these parameters with the key determinant appearing to be the peak movement rate of the landslide during the movement event in question. We propose that the key factor is whether the yield stress is exceeded. If so, rate and state friction may dominate; if not then creep decay may be critical.

1 INTRODUCTION

Landslides are a pervasive hazard on the surface of the earth, responsible for an average of up to 14,000 fatalities per annum (Petley 2012). Triggered primarily by one or more of the effects of precipitation, seismic shaking or slope alteration by humans, landslides also induce substantial socio-economic impacts on society. In many cases these effects are magnified by a lack of insurance cover, resulting from both their socio-economic setting (the majority of loss-inducing landslides occur in comparatively poor countries across Asia and Latin America) and by an unwillingness by insurance companies to provide cover for mass movement hazards in most territories. The latter results from a perceived poor understanding of the geographic distribution of landslide hazard, and the difficulties of determining potential levels of consequential loss. The effects are to increase the impact of landslide hazards relative to other natural hazards.

Whilst the majority of human casualties are associated high velocity landslides, and in particular debris flows, mudflows and soil/rock avalanches, slow moving landslides can cause high levels of financial loss, and, in some cases, loss of life. Thus, understanding these landslides remains a priority. The simple mechanics of these landslides is well-understood in terms of the role of elevated pore fluid pressure leading to a reduction in normal effective stress, and thus failure, and the development of strain, when the yield strength is exceeded. However, observed patterns of movement are more complex than this simple relationship would imply, and are important in terms of understanding, and forecasting, future behaviour for any slow moving landslide. In this paper, the relationship between pore fluid pressure and the rate of movement of landslides is reviewed, demonstrating complex patterns that have hitherto not been fully understood. Interestingly, glaciers display similar behaviour, and a number of hypotheses have been proposed to explain these mechanics across the two types of mass movement. The viability of these models for landslides is examined, and a new framework is proposed to account for the observed complex behaviour in landslide systems.

2 PATTERNS OF MOVEMENT OF SLOW MOVING LANDSLIDES

2.1 A review of landslide movement patterns

It is well established that the movement rate in a slope has a non-linear relationship with pore water pressure (e.g. Bertini, et al, 1984; Gonzalez et al. 2008). In general, once movement has commenced small increments of additional pore water pressure lead to successively greater increases in movement rate; the relationship between pore water pressure and movement rate is sometimes characterised as being exponential. This has sometimes been characterised with a viscosity modification to the Mohr-Columb failure criterion, with some success in predicting the moment patterns of flow type landslides. These models predict a movement rate for any given value of pore water pressure in the landslide, regardless of the dynamic state of that pore water pressure. Of course in reality, factors such as the geometry of the landslide play a key role. Thus, for example, in a rotational landslide the mass becomes increasingly stable as strain accumulates, such that the relationship between strain rate and pore water pressure will change as movement develops (primarily because the static stress state will change). However, in a large landslide this changing relationship will require large strains to become significant.

Some landslides show a simple relationship between pore water pressure and rate of movement in monitoring data. Thus, for example, monitoring of the Vallcebre landslide in the Eastern Pyrenees of Spain showed a simple, non-linear relationship between velocity and the depth of ground water (i.e. the shear surface pore water pressure) (Corominas et al. 1999; Fig. 1). In such cases the movement rate of the landslide can be predicted for any groundwater level.

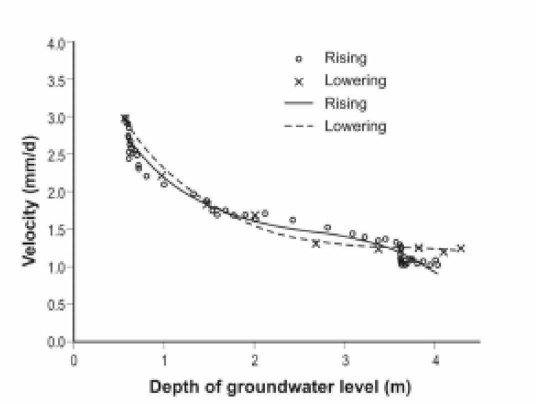

Figure 1: Patterns of movement of the Vellcebre landslide. Data from Corominas et al. (1999). Figure from Massey (2010)

Interestingly, however, there are a number of documented cases in which this relationship has proven to be more complex than might be expected, even when geometric factors have been taken into consideration. In particular, many landslides show a different movement response when pore water pressure is increasing in comparison to when pore water pressure is falling. But, surprisingly, there is no consistent relationship. The following sections provide some examples. Unfortunately though, there is a surprising paucity of published examples in which monitoring data is of sufficient quality to allow this relationship to be examined in detail.

2.2 La Valette landslide, France

La Valette landslide is located close to Saint-Pons in the Barcelonnette basin, in the Alpes-de-Haute-Provence region of France. Movement began in March 1982 as a reactivation of a pre-existing landslide (Van Asch et al. 2007). The landslide consists of an upper rotational slide that transitions into a mudflow as the displaced blocks degrade. It is large – the estimated volume is about 3.5 x 10^6 m^3, the length is about 2 km and the shear surface depth is 25 to 35 m in the central part of the mudflow. The landslide moves at variable rates, with a total displacement rate of about 1 to 2 m per annum.

La Valette landslide is extensively monitored due to the threat that it poses to the community at the foot of the slope. Van Asch et al. (2007) presented monitoring data for the landslide during a phase of increased pore water (Fig. 2). As expected they found a non-linear relationship (hysteresis) between movement rate and groundwater level, but perhaps less predictably they also found that the movement rate when the ground water was increasing was substantially different from that when groundwater level was declining. In this case a rising groundwater level was associated with a higher movement rate than was the case with a falling groundwater level. This was found to be consistent across two substantial periods of movement. This behaviour appears to be a complex version of strain hardening, in which resistance to movement increases with deformation. In this paper we refer to this style of relationship between movement rate and pore water pressure as strain hardening behaviour. Note however that this is a more complex style of behaviour than is normally ascribed to strain hardening as the increased resistance appears to develop at the point at which pore water pressures start to fall, but not before.

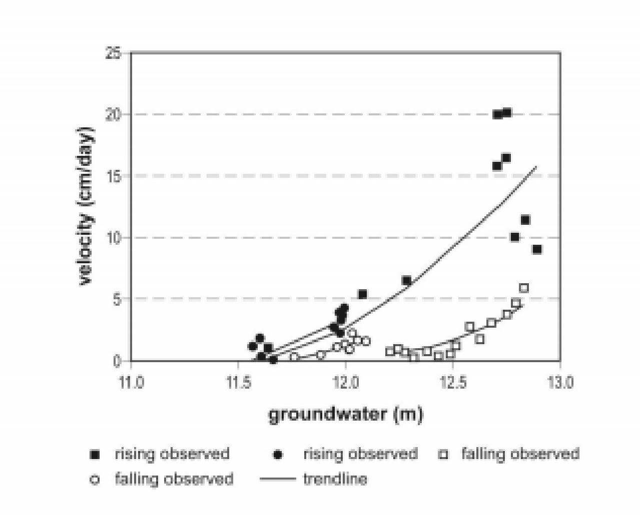

Figure 2: The relationship between velocity and groundwater level (depth above the shear surface) for La Vallette landslide. Data from Van Asch et al. (2007), figure from Massey (2010)

Similar behaviour has been seen in other landslides. Thus for example, Bertini et al. (1986) saw strain hardening behaviour at the Fasio San Martino landslide in Central Italy.

2.3 A reactivated landslide in central Japan

Matsuura et al. (2008) monitored both pore water pressures and landslide displacement in an unnamed reactivated landslide in weathered mudstone and silty sandstone in central Japan. This landslide was about 400 m long and 50 to 70 m wide. Movement occurred in response to increased pore water pressures driven by both precipitation and snowmelt. The basal shear surface, which was at a depth of 4 to 7 m, lay in highly weathered tuff. This was a comparatively fast moving landslide – rates of up to 50 mm per day were recorded – and between 9th September and 3rd December 1992 the landslide moved a total of about 1290 mm. During phases of increased rates of displacement the landslide displayed a strong pattern of hysteresis in the relationship with pore water pressure, but in the opposite sense to that displayed by La Valette (Fig 3). In this case displacement rates were comparatively slow as pore water pressure increased, and more rapid as it decreased. Particularly interesting is the observation that the landslide continued to accelerate even as pore water pressure started to fall. We term this a strain weakening behaviour, in which the landslide shows increased susceptibility to movement as strain develops, although once again the pattern of behaviour may be more complex than simple strain weakening would imply. In the case of the unnamed C. Japan landslide, this strain weakening behaviour was displayed in several movement periods. Matsuura et al. (2008) were not able to explain this behaviour, but suggested that it might be controlled by the geometry of the landslide:

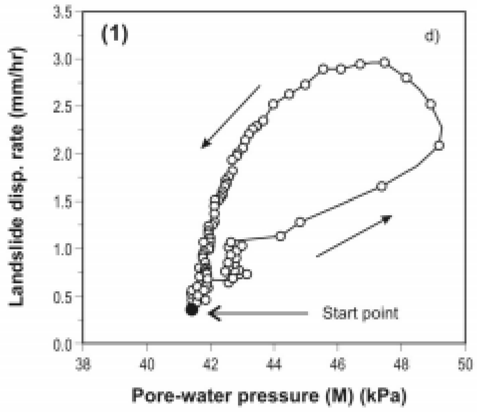

Figure 3: The relationship between the landslide displacement rate and the pore water pressure for the C. Japan landslide. Data from Matsuura et al. (2008),

"One reason for this may be that some aspects of landslide kinematics are controlled by the inclination of the sliding surface and the interaction between the moving body and side in the surrounding stable ground."

It is unclear as to how this mechanism would operate in a landslide of this type.

2.4 The behaviour of the Kualiangzi landslide in China

The Kualiangzi landslide on the margin of the Sichuan Basin of central China is a deep-seated translational bedrock landslide in interbedded mudstones and sandstones (Xu et al. 2016). This landslide is very large, with a width of about 1,100 metres and a length of up to 390 m, with an estimated volume of about 25.5 million m^3. Movement occurs on an inclined shear surface in weathered mudstone located an average of 50 m below the surface. At the rear of the landslide there is an exceptionally large tension trough.

Xu et al. (2016) monitored movement on the landslide through 2013, finding that the displacement rate of the landslide increased in response to precipitation. Analysis of the movement of the landslide record suggests that it broadly shows the strain hardening type of behaviour (Figure 4). Interestingly, the two movement events represent different failure regimes – in the case of the first movement event, the calculated factor of safety of the landslide did not drop below unity. In the second movement event this was the case (Xu et al. 2016 suggested that it reached about Fs=0.93). Nonetheless in both cases the landslide showed the strain hardening style of behaviour.

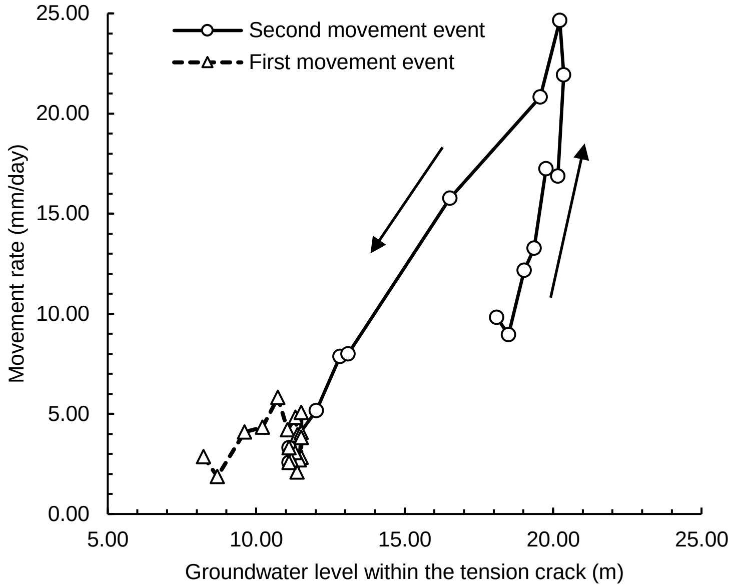

Figure 4: The relationship between the movement rate and the groundwater level in the Kualiangzi landslide, after Xu et al. (2016)

2.5 The behaviour of the Ventnor landslide in southern England

Amongst many other studies (e.g. Hutchinson and Bromhead 2002), Carey (2011) investigated the behaviour of the large (700 hectare), slow moving landslide complex upon which the town of Ventnor is built in the Isle of Wight in southern Britain. This is a complex landslide, involving differential block movement and the opening of grabens, on a very deep (>100 metre) shear surface (Hutchinson and Bromhead 2002). Movement rates are very low however, with peak velocities below 1 mm / day. This very large landslide has been extensively monitored, in particular in the area of a large graben structure that is developing at the crown of the landslide. At this location, both pore water pressure and displacement have been measured at various times.

A notable movement event occurred in the winter of the year 2000 in response to a prolonged and unusually wet period of weather. In this case, the strain weakening style of behaviour was clearly observed (Fig. 5), with movement rates being considerably higher on the falling limb than when pore water pressures were increasing.

2.6 The response of glaciers

Interestingly, it has long been observed that some glaciers also show hysteresis in movement in response to stress changes (Iken et al. 1983 for example). Shallow glaciers are in many ways landslides of ice, with sliding occurring either on a bedrock – ice interface or through deformation of a layer of till between the ice and the bedrock. An advantage of glacers is the relative ease with which the basal processes can be investigated (certainly in comparison with landslides), as it is sometimes possible to access the basal region. Considerable work has been undertaken to understand their dynamics.

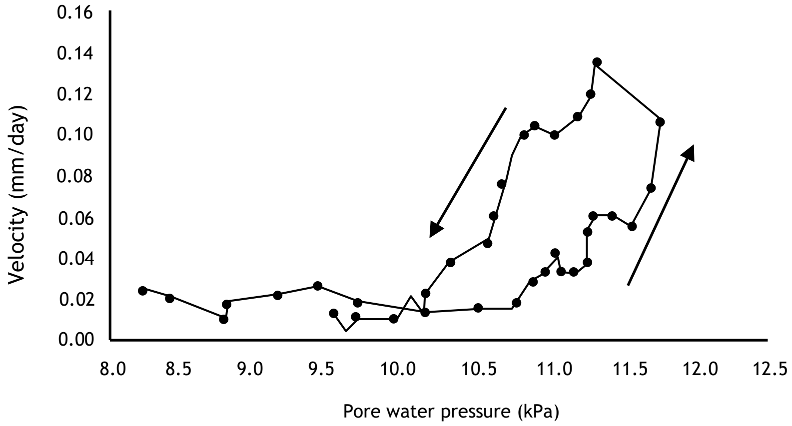

Figure 5: The relationship between landslide velocity and pore water pressure for the Ventnor landslide, after Carey (2011)

Basal tills show creep like behaviour below the yield strength, and a combination of creep and stick-slip behaviour (representing periods in which the effective normal stress reduces sufficiently to ensure that the macroscopic yield strength is lower than the externally imposed shear stress) results in a stepped movement pattern, in common with landslides. A key finding in till dominated systems is that creep rates often decay rapidly under constant stress forcing, once the initial perturbation that caused the movement to start has passed. Thus, till deformation provides a potential mechanism to explain this behaviour; creep rates have been observed to increase so long as normal effective stress is increasing, but decline under constant stress conditions. In a real system this would generate the strain hardening style of behaviour.

Glaciers examined by Damsgaard et al. (2016) shows this behaviour, with slow increases in velocity during phases of increasing pore water pressure, but rapid reductions in movement rate when pore water pressures peak. The authors point out that behaviour that is similar to that of glaciers is seen in landslides, and hence argue that the styles of deformation are directly analogous.

2.7 Insights into landslide response to pore water pressure change from laboratory testing

Most laboratory testing of landslide materials does not provide insight into the response of materials to changes in normal effective stress. The vast majority of geotechnical tests use a non-representative stress path, in which deformation is driven by changing shear stress under conditions of constant strain rate. In drained tests, normal effective stress is not permitted to change; in undrained tests pore water pressure can be generated, but only as a response to the application of shear stress. To investigate the behaviour described above requires the use of the field stress path, sometimes termed the pore pressure reinflation (PPR) test (see Petley *et al.* 2005), in which normal and total effective stress are kept constant, and pore water pressure is varied. The PPR test is most commonly undertaken within triaxial or stress path equipment, which makes it simple to capture the pore water pressure increase phase, but challenging to deal with the subsequent reduction in pore water pressure conditions. Nonetheless this equipment can provide considerable insight.

Ng (2007) undertook a large suite of PPR tests on undisturbed residual soil samples from Lantau Island in Hong Kong. Some of these experiments involved a step-wise increase in pore water pressure (and thus a reduction in normal effective stress) with axial stress and confining pressure held constant, initially at less than the yield stress, but ultimately exceeding it. Fig. 6 shows the development of strain rate in two tests, for one of which pore water pressure was increased in steps of 10 kPa, once per hour, whilst in the other pore water pressure was increased constantly (ramped) at 10 kPa per hour. In the ramped test the strain rate increased exponentially with increasing pore water pressure (i.e. decreasing effective stress state). However, in the stepped test the strain rate initially increased at a rate substantially higher than that of the other test, but which subsequently declined. This initially high and then declining creep rate is a manifestation of the creep decay mechanism. This behaviour, which was seen consistently in the tests of Ng (2007), is similar to that observed in the till deformation of glaciers.

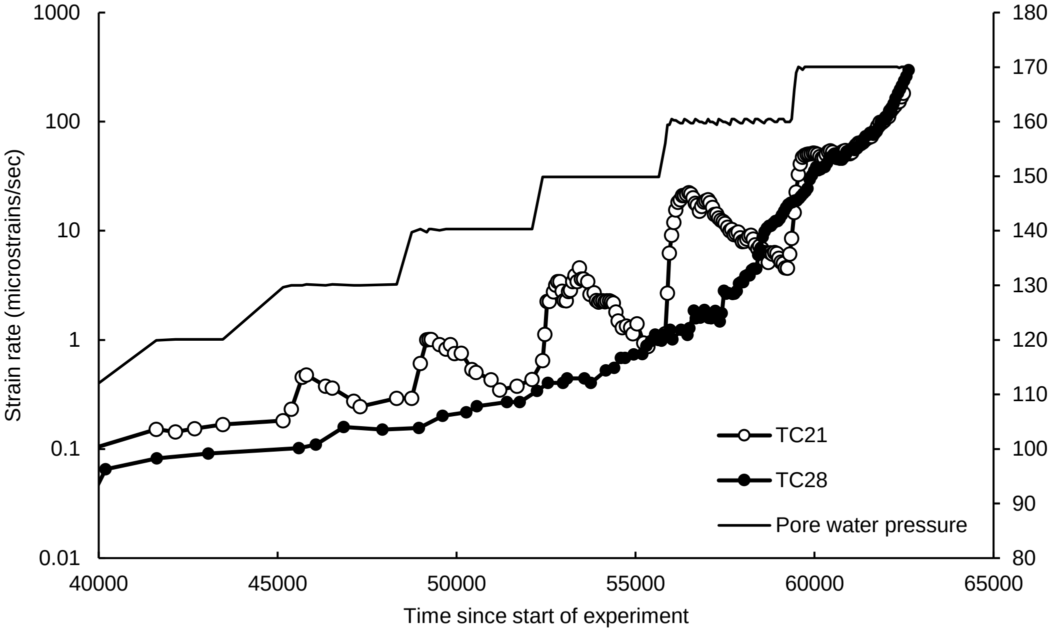

Figure 6: PPR experiment results for residual soil samples from Lantau, Hong Kong, after Ng (2008). Sample TC21 was subjected to increases in pore water pressure in 10 kPa steps (illustrated on the graph), whilst for sample TC28 porewater pressure was increased at the same average rate, but at a constant rate

The initiation of final failure in these tests was also interesting. After the final pore water pressure step the stepped test sample (TC28) showed an initial increase in strain rate (Fig. 7), which then declined before increasing again, with the sample then proceeding to full failure. This appears to be evidence that the final failure event is associated with damage accumulation, as postulated by Petley et al. (2002). Interestingly, Carey and Petley (2014) saw similar behaviour, with final failure being observed in a long term creep test in which no change in effective stress state occurred.

3 DISCUSSION

From the examples described above, and from others in the literature (Table 1), is clear from a range of landslides that different patterns of movement can be seen in response to changes in pore water pressure. In all cases the relationship between movement rate and pore water pressure is exponential once FoS≤1, but for some landslides the relationship may be considered to be strain hardening, in others strain weakening, whilst in a small number the behaviour may be strain neutral, or the response to pore water changes is weak (e.g. Taihape and Utiku). In none of the studies outlined above was a clear explanation given for the response observed. In all cases in which there were multiple movement events the landslide showed consistent behaviour. Thus, in each case it appears to be a fundamental property of the landslide in question.

The strain hardening style of behaviour has also been observed in glaciers moving through deformation of a basal till. Damsgaard et al. (2016) noted the similarity in behaviour seen between glaciers and some landslides. In the case of the glaciers that they modelled, creep was a distributed mechanism whilst slip involved some degree of strain localisation. Whilst a creep decay mechanism was observed, this applied below the critical shear stress. Interestingly, Damsgaard et al. (2016) also note that above the yield strength the rheology of the systems becomes rate independent. This view does not seem to be supported by the monitoring data for the landslides.

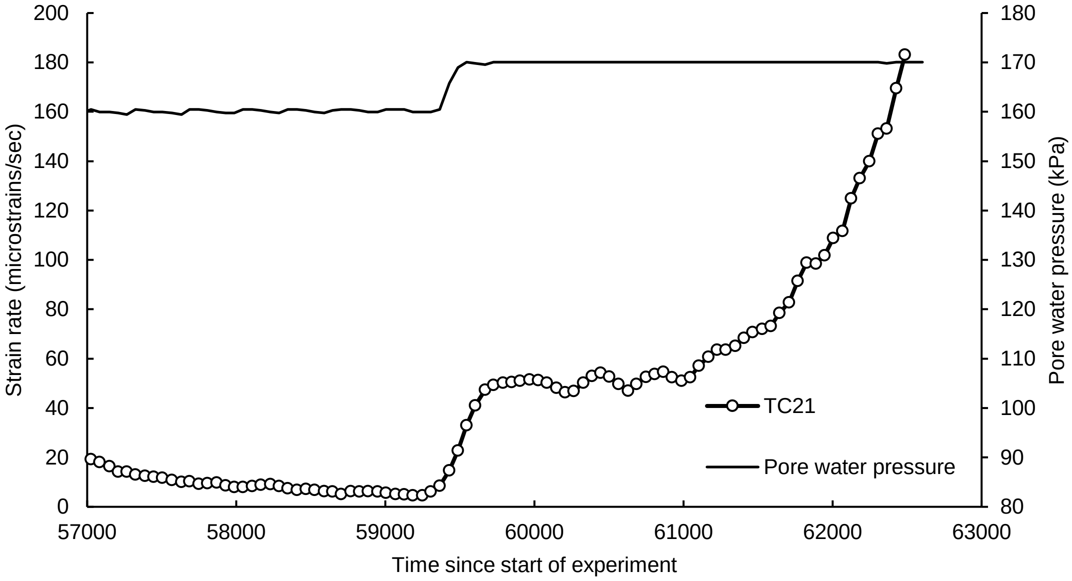

Figure 7: Detail of the last phase of the experiment on sample TC21, after Ng (2008).

Van Asch et al. (2017) described the strain weakening style of behaviour as a lower intrinsic viscosity and lower dependency on excess pore water pressure when the pore water pressure is rising. They noted that intrinsic viscosity is not necessarily a constant value, but recognised that a decrease in viscosity after pore water pressures have peaked is hard to explain. They propose that this may be an effect of the size of the landslide body, with different parts of the mass experiencing extension and compression at different times. This may explain a complex response to fluctuations in pore water pressure at any point in the landslide.

The various landslides for which there is adequate monitoring data to determine hysteresis behaviour in response to changes in pore water pressure are listed in Table 1 in order of peak movement rate. No obvious relationship between the pattern of movement described in the paper and landslide type or material can be seen, but there does appear to be a general relationship in terms of movement rate. On the whole (but not in every case), landslides with high movement rates show a strain weakening pattern (typically >20 mm / day), whilst those with low movement rates (typically <10 mm/day) show the strain hardening pattern. The exception to the latter is the Ventnor landslide, but note that this movement record is from the graben structure at the crown of the landslide, where the stress regime and deformation pattern may be highly complex.

This behaviour may be explainable by considering the deformation state. We hypothesise that slow rates of landslide deformation in these systems are typically occurring within the creep domain, where the dominant mechanism is plastic deformation through interparticle movement. In this domain, the creep decay mechanism suggests that under constant stress states the creep rate will decline; this behaviour is also seen in the experiments of Ng (1999) and in the behaviour of glaciers. Given this creep decay mechanism, it is inevitable that a reduction in pore water pressure will induce a dramatic reduction in the rate of movement.

Table 1: A summary of the landslide movement records analysed in this paper

Name	Landslide type	Basal material	Peak movement rate (mm/day)	Pattern	Reference
La Valette	Translational mudflow	Weathered soil	200	SH	Van Asch et al. (2007)
Purbeck	Mudslide	Weathered clay	60	SW	Allison and Brunsden (1990)
C. Japan	Translational rockslide	Mudstone /silt	50	SW	Matsuura et al. (2008)
Kualiangxi	Translational rockslide	Clay	25	SW	Xu et al. (2016)
Slumgullion	Earthflow	Clay-rich debris	10	Neutral/SH	Schulz et al. (2009)
Utiku	Translational rockslide	Weathered clay	3.0	SH (? Role of pore water)	Massey et al. (2013)
Vallcebre	Translational rockslide	Colluvium	1.5	Neutral	Corominas et al. (1999)
Fasio San Martino	Earthflow	Clay-rich siltstone	0.4	SH	Bertini et al. (1986)
Taihape	Translational rockslide	Weathered clay	0.1	SH (? Role of pore water)	Massey et al. (2016)
Ventnor	Rotational rockslide	Weathered clay	0.1	Neutral / SW	Carey (2011)

On the other hand, the more rapid movement rates, and those associated with faster glacial movement, are associated with the strain weakening mechanism. In this case, Dansgaard et al. (2016) note that in glaciers and landslides this may well be associated with a localisation process that occurs once the yield stress has been exceeded. We propose that the key mechanism here is a rate dependent friction law that allows resistance to movement to change once movement has been initiated. Such a rate-dependent friction process, in which friction reduces with increasing movement rate, as outlined in Handwerger et al. (2016) would generate a strain weakening pattern of movement. On the other hand, a state and rate dependent friction law could also allow the development of strain hardening behaviour under the right circumstances.

As a consequence, the different styles of behaviour seen in landslides in response to changes in pore water pressure, and thus to the normal effective stress state, is probably related to two different processes. Below the yield stress, creep mechanisms dominate. In this case, the creep decay mechanism is critical, in particular when pore water pressures start to fall. In these circumstances, creep rate rapidly declines, causing the strain hardening style of behaviour to be displayed. On the other hand, above the yield stress rate and state dependent friction dominates, allowing both strain weakening and strain hardening styles of behaviour to be shown. In both cases, behaviour may be modified by local conditions associated with the geometry of the landslide, such as curvature of the shear surface and stress transfer between blocks.

4 CONCLUSIONS

Through a review of the literature we have shown that the relationship between pore water pressure / normal effective stress and the rate of movement of landslides is complex. Beyond the yield stress the movement rate generally has an exponential relationship with normal effective stress. However, it is also clear that the rate of movement may be different between increasing and decreasing pore water pressure states. We have demonstrated that during phases of slow movement landslides tend to show a strain hardening style of behaviour, whilst rapidly moving slide tend to show the strain weakening style. We suggest that this may be associated with the presence of two different mechanisms – below the yield stress creep mechanisms dominate, and thus the effects of creep decay mean that strain hardening is likely. On the other hand, above the yield stress, rate and state dependent friction becomes important, meaning that both the strain weakening and strain hardening styles of behaviour can be shown, depending on the frictional properties of the basal material.

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