Influence of Transient Pore Pressures on the Progressive Failure of Rock Slopes

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1. Introduction

The concept of strength degradation and progressive failure represents an important advancement in our understanding of deep-seated rock slope failure. Conventional stability analyses generally assume the strength of a rock mass to be constant, explaining failure relative to a single trigger such as a heavy precipitation event. In doing so, these analyses fail to explain the temporal nature of slope failure as seen in monitoring data. Data shows that slope movements are intermittent, correlating with seasonal precipitation patterns and groundwater recharge (Crosta & Agliardi 2003; Cappa et al. 2004; Eberhardt et al. 2004; Bonzanigo et al. 2007). Acceleration and deceleration phases are often observed leading up to failure; however, it is not always clear why certain acceleration phases reach alarming levels without a clear trigger (i.e., in the absence of an exceptional precipitation event) or without failing. To understand this behavior, progressive failure concepts relating to rock strength degradation and strain (Saito 1965; Fukuzono 1985; Eberhardt et al. 1999) can be applied to the influence of non-persistent natural fractures, intact rock bridges, brittle fracturing, and internal shearing at the rock mass scale (Eberhardt et al. 2004; Eberhardt 2008).

Superimposed on this are seasonal precipitation and groundwater infiltration patterns. Recent investigations utilizing advanced numerical modeling techniques show that transient pore pressures cause localized reductions in effective stresses along fractures promoting slip, which in turn triggers slip of adjacent fractures and/or the rupture of intact rock bridges (Eberhardt et al. 2016; Preisig et al. 2016). Over time, this repeated pattern gradually weakens the slope. Occasionally, acceleration episodes involving extreme slope movements occur but these do not necessarily scale with the size of the precipitation event(s). This introduces significant uncertainty in early warning monitoring; acceleration events may either be an early warning of impending failure, or a false alarm related to localized movements that eventually lock up and return to background levels. The results presented will demonstrate how slope displacement monitoring and modeled groundwater fluctuations can be used to calibrate numerical models and establish the degree of criticality present in a slope. The modeling of seasonal variations further enables reference to be made to time in calculations that are otherwise limited to stress-strain behavior. This provides a means to assess displacement rate thresholds at which behavior change may occur for a given failure mode, which in turn can be used to establish and constrain early warning alarm thresholds.

2. Rock Slope Responses to Transient Pore Pressures

Many of the external factors, aside from gravity, that promote deep-seated rock slope movements affect the rock mass in a cyclical manner. For example, climatic factors like seasonal wet periods transitioning into seasonal dry periods act to raise and lower the piezometric levels and pore pressures in a slope. Bonzanigo et al. (2007) showed for the Campo Vallemaggia landslide in Switzerland that rising piezometric levels in the slope in response to seasonal rain and snowmelt resulted in accelerating slope movements, which would then subside to movements below the detection threshold associated with steady state creep (Fig. 1a). This is a common observation in rock slope early warning monitoring (Figs. 1b-d). However, the velocities encountered can be variable. Velocities associated with acceleration events can range from millimeters to tens of centimeters per day; in some cases, the accelerating behavior results in catastrophic failure, while in other cases it self-stabilizes and returns to background levels. The results are problematic for early warning forecasting where accelerating slope displacements are taken as a sign of imminent failure. In Figure 1, several periods of accelerating behavior are highlighted that coincide with periods of increased pore pressures. However, outside of the causal relationship between increasing pore pressures and accelerating slope behavior, it can be noted that the pore pressures in each case are not exceptional relative to those observed before or after.

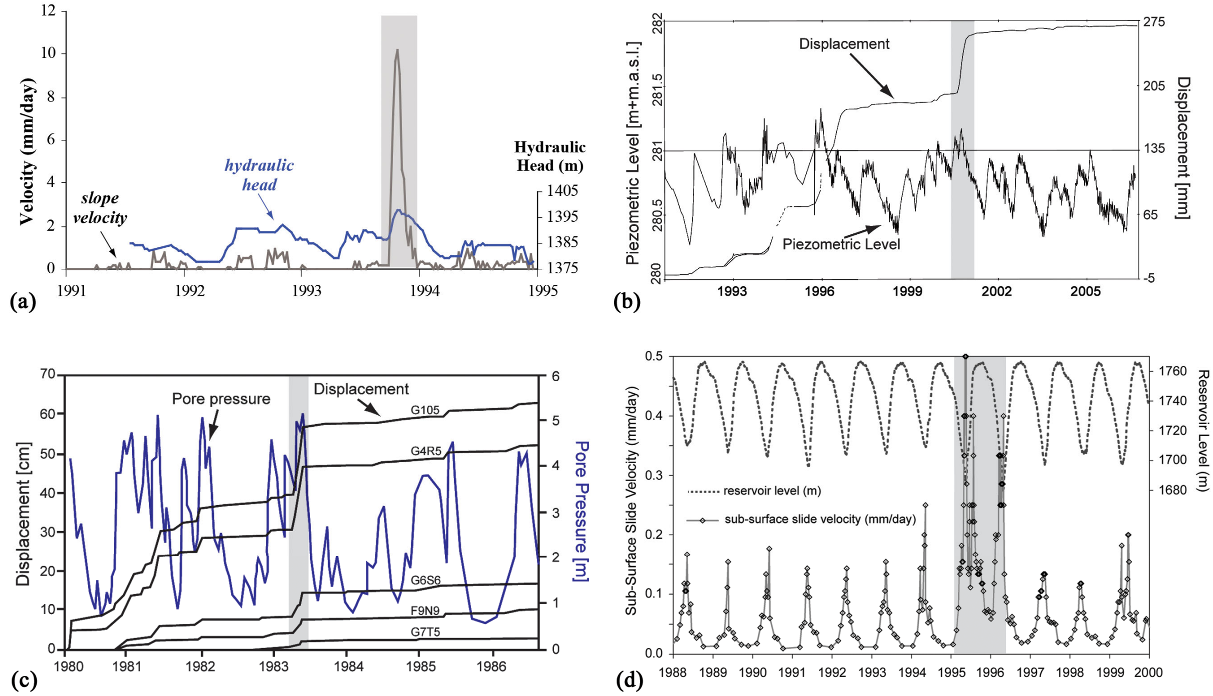

Figure 1. Examples of intermittent slope behavior correlated with cyclic changes in hydraulic pressures: (a) Campo Vallemaggia landslide, Switzerland (Bonzanigo et al. 2007); (b) Brewery Creek landslide, New Zealand (Macfarlane 2009); (c) Sallèdes landslide, France (Vuillet & Hutter 1988); and (d) Hochmais-Atemkopf landslide, Austria (Zangerl et al. 2010). The superimposed grey intervals indicate substantial acceleration events without exceptional triggering events. Note that the first three cases (a-c) are driven by seasonal precipitation patterns, whereas the fourth case (d) is an example where the intermittent behavior is correlated to fluctuating water levels in a dam reservoir. After Preisig et al. (2016).

3. Progressive Failure and Hydromechanical Fatigue

The variable slope displacement responses to transient pore pressures observed in Figure 1 can be explained using the concept of hydromechanical fatigue (Preisig et al. 2016), in which transient pore pressures act to locally reduce effective stresses along fractures promoting slip. This in turn causes stress transfer and brittle failure of intact rock bridges that gradually weakens the rock slope leading to its progressive failure. The brittle failure of intact rock bridges also contributes to increasing connectivity of groundwater flow pathways and increasing fracture permeability through shear slip and aperture dilation (Preisig et al. 2015).

These principles can be applied using distinct-element bonded-block modeling techniques. Figure 2 shows the results from a model of a steep rock slope in jointed andesite that forms the abutment to a dam. The modeled rock mass incorporates the key natural fracture sets mapped in the field, which include a slope parallel set dipping at 60° with high persistence, a conjugate set dipping into the slope, and a series of non-persistent joints dipping out of the slope with an angle of 35°. Because of the limited persistence of these joints, considerable strength is provided in the form of intact rock bridges. The constitutive models for the blocks and natural fractures were both selected to allow for post peak strength loss arising from either slip along the joints or brittle fracturing of the blocks. A water table was implemented in the model representing seasonal low and high precipitation and reservoir levels; one cycle from the low to high levels and back again was equated to one year. The model is calibrated to an 8-year record of slope monitoring data. Results are shown in Figure 2 for the cumulative damage state and corresponding slope displacements at 10 and 120 years. The cumulative displacement trend in Fig. 2b show a relatively consistent rate of approximately 5 cm/year for more than 100 years, with small acceleration events coinciding with each seasonal high. However, the small incremental increases in damage and internal shearing eventually accumulate to the point that a deep-seated step-path rupture surface begins to localize and the slope velocity doubles to approximately 10 cm/year (Year 115 in Fig. 2b). Slope velocities then continue at this higher rate until Year 120 when the full slide mass suddenly mobilizes and fails catastrophically.

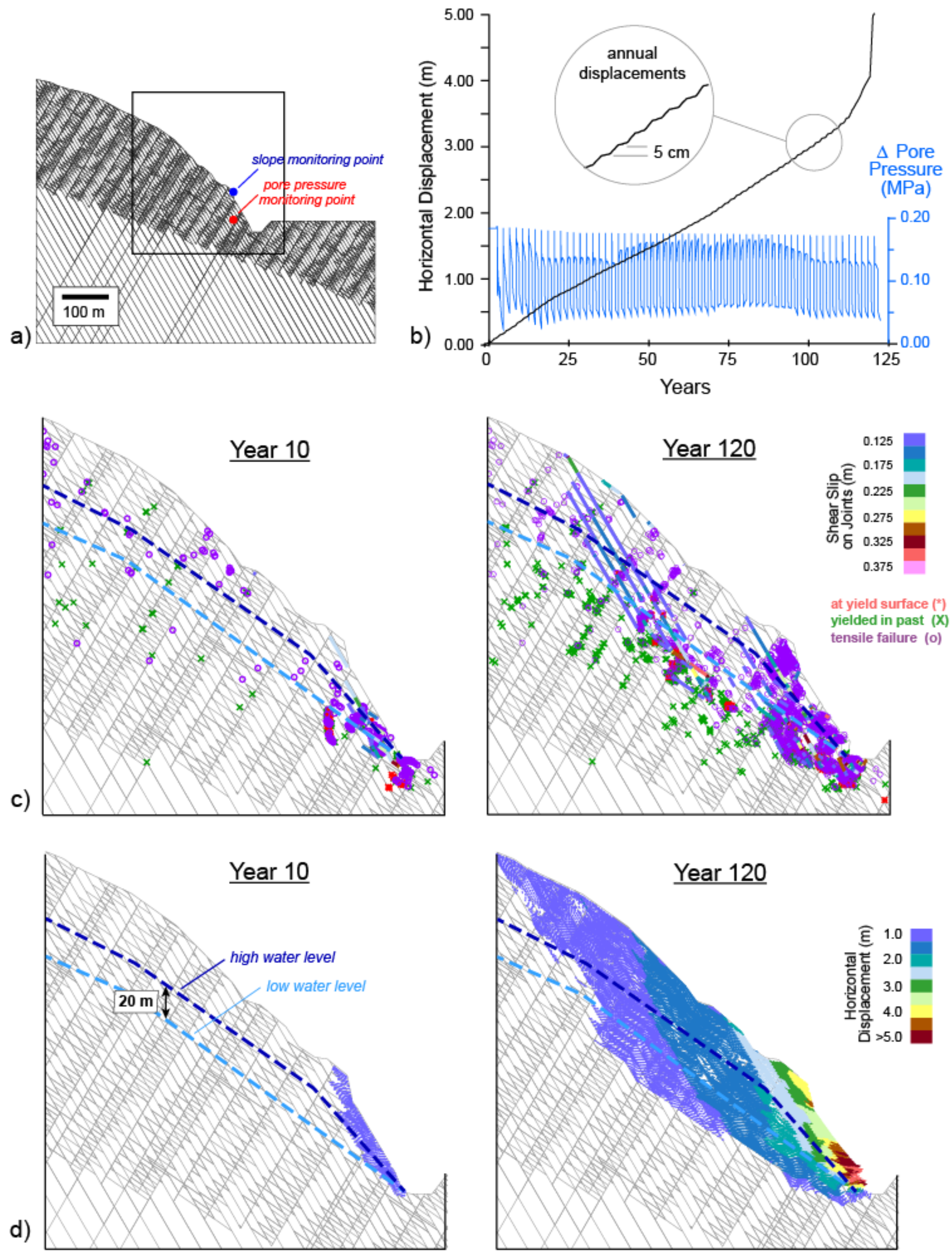

Figure 2. Distinct-element modeling of hydromechanical fatigue leading to progressive failure and rock slope collapse: a) model geometry, location of monitoring points, and window used to present close-up results; b) modeled pore pressure and displacement histories for the indicated monitoring points; c) comparison of shear slip on joints and rock slope damage/rock bridge failure in Year 10 (early development) and Year 120 (localization of rupture surface); and d) corresponding horizontal displacements.

4. Path Forward

The results in Figure 2 explain the capacity of a deep-seated rockslide to remain at or near background levels of activity over an extended period of time, and then enter into a phase of critical acceleration. These reactivation periods are unpredictable and cannot be evaluated via conventional stability analyses. Instead, advanced numerical modeling techniques integrating damage and post-peak strength degradation behavior can provide assessments of intermittent slope movements and sensitivity to repeated acceleration events that may lead to forecasts of catastrophic failure potential. These must be informed and constrained by geological mapping and rock mass characterization data, and calibrated against geotechnical monitoring data.

The suggestion that deformation rates depend on a slope's damage state has practical implications for the interpretation of monitoring data. The relationship between deformation rates and seasonal pore pressure changes can be used to calibrate numerical models and establish the degree of damage and criticality present in the slope. The modeling of seasonal variations further enables reference to be made to time in calculations that are otherwise limited to stress-strain behavior. This results in a means to assess displacement rate thresholds at which behavior change may occur for a given failure mode, which in turn can be used to establish and constrain early warning alarm thresholds.

Experience using the above modeling approach indicates that the time to rock slope collapse is dependent on the steepness of the rupture surface that localizes, which in turn is dictated by the natural fracture network present (i.e., rock mass fabric) and related kinematics. The corresponding mobilized volume is dominated by active driving forces, with passive resistance being largely restricted to a small volume at the slope's toe. Over time, the active driving forces remain relatively constant but the passive resistance incrementally decreases as fatigue damage accumulates reducing rock mass cohesion and facilitating toe breakout. This results in an unstable condition where accelerating behavior (i.e., behavior change) is likely to serve as a precursor to catastrophic failure.

Another key controlling factor is the rock strength, its heterogeneity, and its sensitivity to other strength degradation processes (e.g., weathering; Eberhardt et al. 2005) or to other triggers (e.g., earthquakes; Gischig et al. 2016). To properly model the localization of a rupture surface leading to progressive failure, strain-dependent rock mass strength values are required (Eberhardt 2008). Some initial guidance has been derived from Eberhardt et al. (1999, 2004) where strain-dependent values of cohesion and friction have been estimated from acoustic emissions and strain measurements from laboratory testing; but these are for intact rock. It can be argued that intact rock strength is actually more appropriate for the strength degradation of intact rock bridges, but more research is required to validate this and increase confidence in the reliability of the model parameterization and calibration process.

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