Deciphering Landslide Behavior Using Large-scale Flume Experiments

Mark E. Reid (U.S. Geological Survey) · Richard M. Iverson (U.S. Geological Survey) · Neal R. Iverson (Iowa State University, USA) · Richard G. LaHusen (U.S. Geological Survey) · Dianne L. Brien (U.S. Geological Survey) · Matthew Logan (U.S. Geological Survey)

Abstract. Landslides can be triggered by a variety of hydrologic events and they can exhibit a wide range of movement dynamics. Effective prediction requires understanding these diverse behaviors. Precise evaluation in the field is difficult; as an alternative we performed a series of landslide initiation experiments in the large-scale, USGS debris-flow flume. We systematically investigated the effects of three different hydrologic triggering mechanisms, including groundwater exfiltration from bedrock, prolonged rainfall infiltration, and intense bursts of rain. We also examined the effects of initial soil porosity (loose or dense) relative to the soil's critical-state porosity. Results show that all three hydrologic mechanisms can instigate landsliding, but water pathways, sensor response patterns, and times to failure differ. Initial soil porosity has a profound influence on landslide movement behavior. Experiments using loose soil show rapid soil contraction during failure, with elevated pore pressures liquefying the sediment and creating fast-moving debris flows. In contrast, dense soil dilated upon shearing, resulting in slow, gradual, and episodic motion. These results have fundamental implications for forecasting landslide behavior and developing effective warning systems.

Keywords. Landslide, experiment, failure behavior, hydrologic trigger, critical state, porosity

1. Introduction

Some landslides accelerate catastrophically with potentially lethal consequences, whereas others creep intermittently downslope, perhaps causing property damage but rarely fatalities. Rainfall patterns that initiate slide motion vary as well. Some slides require prolonged rainfall to instigate motion, yet others occur following short, intense rain bursts. Such profound differences in behavior have fundamental implications for designing mitigation strategies, implementing effective warning systems, and reducing risk.

Precise evaluation of the causes of diverse landslide behavior is difficult because controlling effects cannot be isolated in the field; this limits our understanding of landslide dynamics as well as our prediction capabilities. Previous studies have attempted to induce failure on natural hillslopes, with varying degrees of success (Harp et al. 1990; Cooper et al. 1998; Ochiai et al. 2004). Other studies have relied on small-scale laboratory tests or experiments to infer landslide behavior (Eckersley 1990; Wang and Sassa 2001; Okura et al. 2002; Take et al. 2004).

As an alternative to field investigations and small-scale experiments, we used the U.S. Geological Survey (USGS) debris-flow flume in Oregon, USA to perform controlled, large-scale landslide initiation experiments. This flume allows us to create landslides similar to small natural failures, but without the scale limitations of typical laboratory tests.

Our experiments focused on deciphering the influences of various hydrologic triggers and differing initial soil porosities on failure style, timing, and subsequent landslide acceleration. We examined three hydrologic conditions that can initiate landslide movement, including: groundwater exfiltration into soil from bedrock, prolonged rainfall infiltration, and bursts of intense rainfall (Reid et al. 1997). We also systematically investigated the effects of initial soil porosity (n) on landslide dynamics at a field scale. A well-established maxim of soil mechanics holds that failure behavior during shear depends on the initial soil porosity (or void ratio) relative to a specific critical-state porosity (Schofield and Wroth 1968). Saturated soils looser than critical state contract as they shear, thereby elevating pore pressures and inducing rapid flow. Soils denser than critical state dilate as they shear, temporarily reducing pore pressures and retarding motion.

Here, we briefly describe some of our landslide initiation experiments, document the effects of different hydrologic triggers, and illustrate landslide behavior derived from different initial soil porosities. We conclude by discussing some implications of these results for predicting landslide behavior and developing effective warning systems.

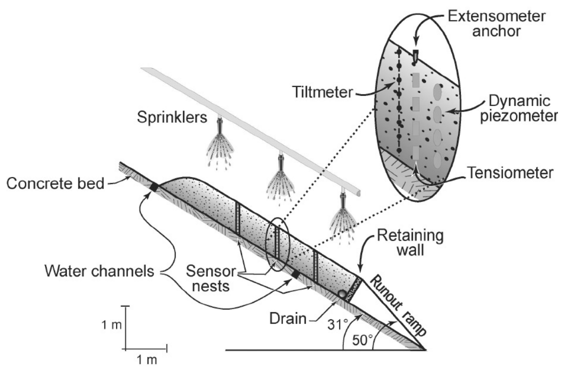


Fig. 1 Schematic longitudinal cross section of landslide experiments at the USGS debris-flow flume. The magnified ellipse depicts the positioning of sensors in vertical nests (from Iverson, et al. 2000).

2. Experiment Configurations

In each of six experiments, we induced failure in a 0.65m thick, 2m wide, 6m^3 prism of loamy sand placed behind a rigid retaining wall on the 31° flume bed (Fig. 1). We systematically investigated hydrologic triggering of sliding by either injecting water from channels in the bed (to simulate groundwater exfiltration), by overhead sprinkling (to simulate prolonged or intense rainfall), or a combination of these methods. We investigated differences in the failure behavior of dense and loose soils (relative to critical state) by varying initial soil porosity. To create loose soil, we dumped and raked the loamy sand without further disturbance. To create dense soil, we used controlled vibratory compaction on a sequence of 10cm thick soil layers of the same loamy sand. Further details of the USGS flume configuration can be found elsewhere (Iverson et al. 1997; Iverson et al. 2000).

About 50 sensors monitored at 20 Hz during each experiment included two nests of tiltmeters (total of 17 or 18 sensors) to measure subsurface deformation and slip-surface location, two surface extensometers to measure downslope displacement, three nests of tensiometers (12 total) and dynamic pore-pressure sensors (12 total) to record evolving pore-pressure fields, and three nests of TDR probes (12 total) to detect changes in soil moisture. We also extracted soil samples for laboratory measurements of porosity, shear strength, saturated hydraulic conductivity at various porosities, unsaturated moisture retention characteristics, compressibility, and, in a series of special triaxial and ring-shear tests, the soil's critical-state porosity (n=0.44).

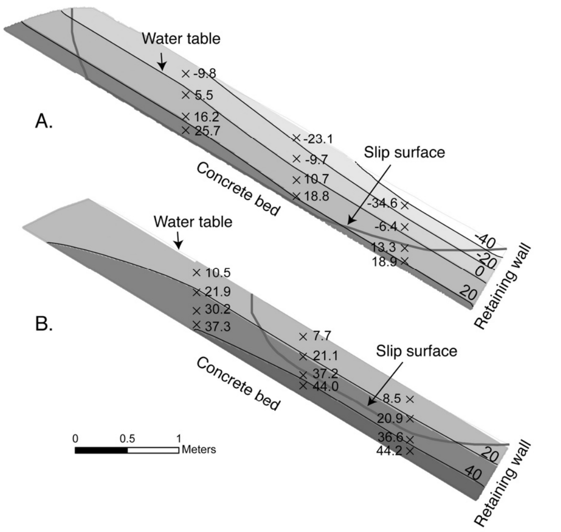
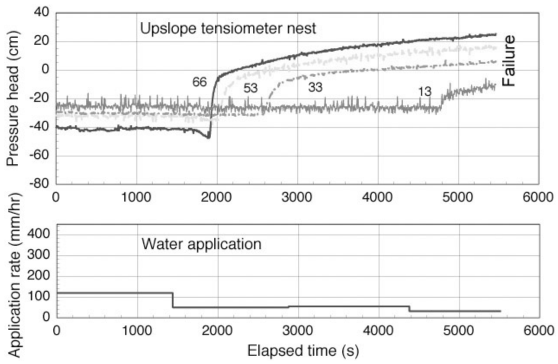


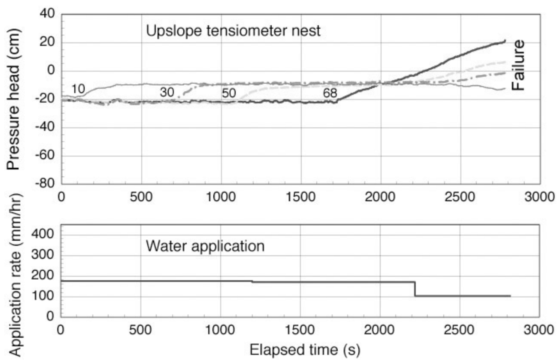
Fig. 2 Cross sections of experimental soil prisms showing slip surface locations, water table locations (zero contour), and pore-pressure heads (cm) at failure. A. Loose soil with groundwater injection. B. Dense soil with both groundwater injection and sprinkling.

3. Hydrologic Conditions Triggering Failure

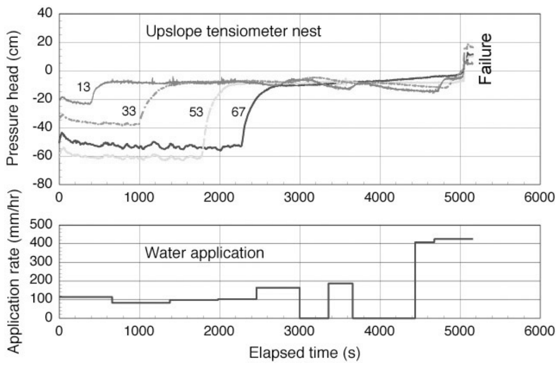
Both precursory and post-failure behavior varied dramatically depending on the initial porosity of the soil relative to its critical-state value. Controlled compaction used in the dense soil experiments resulted in lower hydraulic conductivities and greater shear strengths compared to those with looser soils. Failures in loose soil (n>0.44) typically occurred following about 50-90 minutes of water application, whereas failures in dense soil (n<0.44) usually required 4 to 5 hours of water application. Three experiments with loose soil resulted in nucleation of failure along the concrete flume bed with subsequent propagation of the slip surface upward through the soil prism to daylight near the retaining wall (Fig 2A). Failure often occurred with large parts of the soil partially saturated. In contrast, experiments with dense soil typically produced slip surfaces that nucleated within the soil prism, not along the bed, when positive pore pressures were measured throughout the soil (Figure 2B). With denser soil, both sprinkling and groundwater injection were needed to instigate failure in a timely manner.



A. Groundwater injection



B. Prolonged sprinkling



C. Initial wetting plus intense burst of sprinkling

Fig. 3 Pore-pressure head response and water application rate (normalized for area) for three failure experiments with loose soil. Vertical depths of tensiometers in cm indicated next to lines. A. Response during groundwater injection. B. Response during prolonged sprinkling. C. Response during initial wetting and subsequent intense burst of sprinkling.

In the loose-soil experiments, we were able to induce failure using three distinct water application methods: groundwater injection, prolonged moderate-intensity sprinkling, and initial wetting (without saturation) by moderate-intensity sprinkling followed by a high-intensity burst of sprinkling. Each of these methods resulted in different water pathways, different sensor response patterns prior to failure, and different pore-pressure fields at failure. For example, groundwater injection led to a water table that advanced upward, wetting over half the soil prism before pressures at the bed were sufficient to provoke collapse (Fig. 3A). With moderate-intensity surface sprinkling, an unsaturated wetting front propagated downward until reaching the flume bed, and then a mostly saturated zone built upward, with the highest pressures at the bed at the time of failure (Fig. 3B). With the third trigger using a high-intensity sprinkling burst, pore pressures remained near zero until a rapid rise at failure; this was likely due to a small pressure perturbation from the burst that traveled rapidly downward through tension-saturated soil (Fig. 3C). Failure occurred in the absence of widespread positive pressures after about 10 minutes of intense sprinkling.

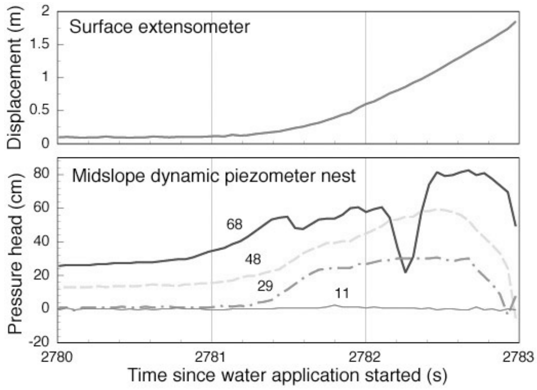
4. Landslide Behavior Following Failure

Our experiments demonstrated that a variety of water application methods and resulting pore-pressure distributions triggered failure, whereas the dynamic behavior following failure was primarily controlled by the initial porosity of the soil. In the loose-soil experiments ($n>0.44$), the dynamic behavior was remarkably consistent. Rapid soil contraction during shearing caused pore pressures to increase dramatically within 1 second as failure began; nearly complete liquefaction failure occurred within 2 seconds as the mass rapidly accelerated downslope (Fig. 4A). As a consequence, all of the loose-soil experiments produced fast-moving debris flows that traveled far downslope (Fig. 5A). Similar collapse behavior has been observed in other landslide initiation experiments using loose soils (Iverson et al. 1997; Reid et al. 1997; Wang and Sassa 2001; Okura et al. 2002; Moriwaki et al. 2004).

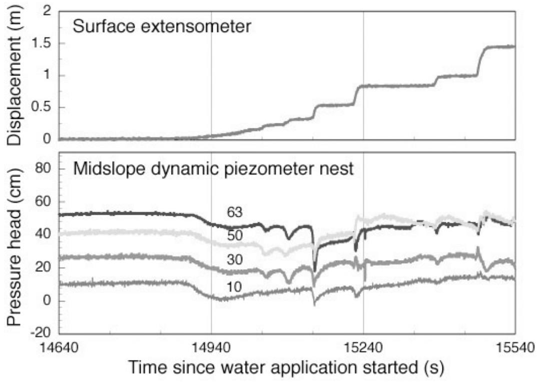
In marked contrast, our experiments with dense soil ($n<0.44$) produced slow-moving landslides. Dynamic behavior during failure in the densest soil consisted of repetitive cycles of slow (< 0.1 m/s) movement, each resulting in modest (< 0.3 m) displacement (Fig. 4B). Each movement cycle started with downslope displacement caused by elevated pore pressures. This displacement provoked soil dilation, a consequent decrease in pore pressures, and a temporary halt in slide movement. The cycle would then repeat, as pore pressures would slowly rebuild, triggering renewed slide displacement. Dilation of the dense soil during shear with concomitant pore pressure decline thereby regulated landslide motion (Iverson 2005). This regulation resulted in a slow-moving landslide with small secondary failures emanating from its toe (Fig. 5B). Video footage showing these dynamic behaviors during experiments conducted in June 1998 and June 1999 can be viewed at http://pubs.usgs.gov/of/2007/1315.

5. Discussion

We used the same loamy sand in each experiment. Our results demonstrate, however, that small variations in initial soil porosity can cause profound differences in landslide behavior, both in the hydrologic conditions triggering failure and in the post-failure dynamic response. Loose soils respond quickly to hydrologic triggering events, and mass failures in these soils can create rapid, potentially lethal debris flows. Dense soils respond more slowly and produce slow-moving landslides sometimes with episodic motion.



A. Loose soil

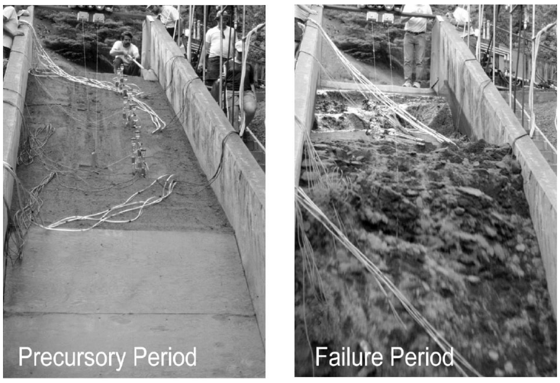


B. Dense soil

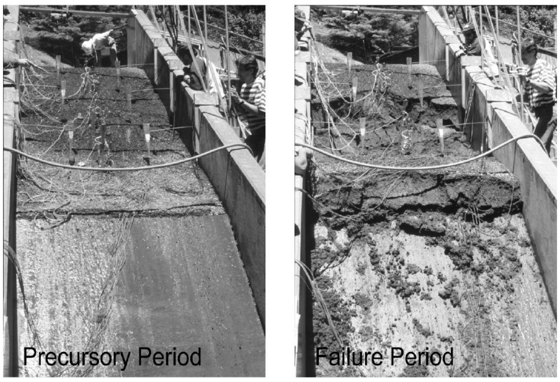
Fig. 4 Pore-pressure head response and surface displacement during two landslide initiation experiments. Note difference in time scales. Vertical depths of piezometers in cm indicated next to lines. A. Rapid failure in loose soil with dramatic rise in pore pressures. B. Slow failure in dense soil with episodic declines in pore pressures and concomitant deceleration.

Recognizing and understanding these differences is crucial for designing effective mitigation strategies and for better forecasting of landslide behavior. For example, differing hydrologic triggers can have strong implications for developing accurate landslide warning systems. Many regional warning systems rely on rainfall intensity/duration thresholds (Keefer et al. 1987). Our results illustrate that different hydrologic processes and different initial soil porosities lead to very different failure times. Thresholds developed for one hydrologic triggering process may not provide accurate warning when other processes instigate landsliding. Moreover, empirical thresholds based on data from multiple triggering processes may be unreliable.

Site-specific landslide monitoring systems often rely on ground-based sensors to detect destabilizing conditions (Reid et al. 2008). Here again, our experiments show that sensor responses leading up to failure can vary considerably (Fig. 3), and clear warning levels that span the gamut of triggering processes could be difficult to define. Our results emphasize that accurate warning systems need to be based on clearly identified landslide processes with appropriate thresholds developed explicitly for those processes. If multiple triggering processes exist, then multiple thresholds may be needed.



A.



B.

Fig. 5 Photographs illustrating landslide behavior during two controlled experiments. A. Behavior of loose soil (n = 0.52) prior to and during rapid failure triggered by groundwater injection. B. Behavior of dense soil (n = 0.41) prior to and during slow, episodic failure triggered by groundwater injection and overhead sprinkling.

Furthermore, effective mitigation strategies go beyond just forecasting when and where slides will occur. Fast-moving landslides are potentially lethal; mitigation strategies for these events are typically quite different than those for slow-moving landslides. Our results indicate that forecasting movement behavior cannot be based solely on material texture (i.e. clay or sand). A primary control is field porosity relative to the soil's critical-state porosity. These cautionary aspects reinforce the need to fully understand landslide processes and to not lump all landslides together when designing hazard mitigation strategies.

Acknowledgments

Work supported in part by grant EAR9803991 from the National Science Foundation. We thank Kelly Swinford and Janet Mann for assistance with these experiments, and Jonathan Godt and Kevin Schmidt for helpful reviews.

References

Cooper MR, Bromhead EN, Petley DJ, Grant DI (1998) The Selborne cutting stability experiment. Geotechnique, 48(1): 83-101

Eckersley D (1990) Instrumented laboratory flowslides. Geotechnique, 40(3): 489-502

Harp EL, Wells WG, Sarmiento JG (1990) Pore pressure response during failure in soils. Geological Society of America Bulletin, 102(4): 428-438

Iverson RM (2005) Regulation of landslide motion by dilatancy and pore-pressure feedback. Journal of Geophysical Research, 110: doi: 10.1029/2004JF000268

Iverson RM, Reid ME, Iverson NR, LaHusen RG, Logan M, Mann JE, Brien DL (2000) Acute sensitivity of landslide rates to initial soil porosity. Science, 290(5491): 513-516

Iverson RM, Reid ME, LaHusen RG (1997) Debris-flow mobilization from landslides. Annual Review of Earth and Planetary Sciences, 25: 85-138

Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WM, Ellen SD, Harp EL, Wieczorek GF, Alger CS, Zatkin RS (1987) Real-time landslide warning during heavy rainfall. Science, 238(4829): 921-925

Moriwaki H, Inokuchi T, Hattanji T, Sassa K, Ochiai H, Wang G (2004) Failure processes in a full-scale landslide experiment using a rainfall simulator. Landslides, 1(4): 277-288

Ochiai H, Okada Y, Furuya G, Okura Y, Matsui T, Sammori T, Terajima T, Sassa K (2004) A fluidized landslide on a natural slope by artificial rainfall. Landslides, 1(3): 211-219

Okura Y, Kitahara H, Ochiai H, Sammori T, Kawanami A (2002) Landslide fluidization process by flume experiments. Engineering Geology, 66(1-2): 65-78

Reid ME, Baum RL, LaHusen RG, Ellis WL (2008) Capturing landslide dynamics and hydrologic triggers using near-real-time monitoring, In: Chen Z, Zhang J, Li Z, Wu F, Ho K (eds) (2008) Landslides and Engineered Slopes: From the Past to the Future, Vol. 1: Taylor & Francis Group, pp 179-191

Reid ME, LaHusen RG, Iverson RM (1997) Debris-flow initiation experiments using diverse hydrologic triggers, In: Chen C (ed) (1997) First International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: ASCE, pp 1-11

Schofield AN, Wroth CP (1968) Critical State Soil Mechanics. McGraw-Hill, New York

Take WA, Bolton MD, Wong PCP, Yeung FJ (2004) Evaluation of landslide triggering mechanisms in model fill slopes. Landslides, 1(3): 173-184

Wang G, Sassa K (2001) Factors affecting rainfall-induced flowslides in laboratory flume tests. Geotechnique, 51(7): 587-599