7th International Conference on Debris-Flow Hazards Mitigation

Debris-flow initiation promoted by extension within a slow-moving landslide

Mark E. Reid[a,*], Dianne L. Brien[a]

[a]U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, CA, 94025, USA

Abstract

The dynamics of slow landslide motion can predispose oversteepened and extended slide regions to debris-flow initiation. For more than 20 years, our real-time monitoring, combined with repeat high-precision GPS surveys, of the Cleveland Corral landslide complex, California, USA, reveals that debris flows initiate from slow-moving kinematic elements of this complex. Different slide elements move in different wet years, and all remain dormant in dry years. To explore controls on landslide-element kinematics, we use triaxial testing to define the critical state behavior of the landslide material, and use a large-diameter sampling ring to determine *in situ* material porosities in both extensional and compressional regions of the slide complex. Regions undergoing extension contain materials looser than their critical state, potentially aiding liquefaction and debris-flow mobilization from shallow, secondary slides. Although intense rainfall serves as a trigger for debris-flow initiation, slow deformation of the larger landslide promotes debris-flow formation by oversteeepening toe and lateral margins and by preferentially extending, and effectively loosening, material in these steep regions.

Keywords: debris-flow initiation; slow-moving landslide; critical state soil mechanics; porosity; GPS; California

1. Introduction

Debris flows initiate from a variety of sources, such as the mobilization of large or small landslides (Iverson et al., 1997; Geertsema et al., 2006; Crosta and Frattini, 2008) or progressive entrainment of sediment during surface runoff (Hungr et al., 1984; Takahashi, 1991; Cannon et al., 2001; Berti and Simoni, 2005; Coe et al., 2008). Within a geomorphic terrain, past movement behavior is often interpreted as forecasting future behavior, i.e. terrain may be prone to either rapid debris-flow initiation or slow-moving landslide deformation. Yet some debris flows initiate from parts of pre-existing, slow-moving landslides (Morton and Campbell, 1974; Reid et al., 2003; Malet et al., 2004; Jibson, 2005; Malet et al., 2005).

In a variety of terrains, locally steep slopes and intense rain can promote debris-flow initiation from landslides when widespread failure and partial or complete liquefaction occur (Iverson et al., 1997). Materials properties, such as porosity and grain-size distribution, can control the propensity for soil to liquefy when sheared during failure. Pervasive soil liquefaction greatly reduces shear strength and thereby enhances debris-flow formation. The application of critical state soil mechanics provides a framework to evaluate the predilection for soils to contract or dilate during shear, when they rearrange to achieve a critical void ratio as a function of the imposed stresses (Schofield and Wroth, 1968; Wood, 1990; Houlsby, 1991). Soils with an initial void ratio (or porosity) greater (looser) than their critical state void ratio contract during shear, increasing pore-fluid pressures and aiding liquefaction. In experimental studies, contractive behavior has been shown to aid debris-flow mobilization from landslides (Iverson et al., 2000; Okura et al., 2002; Olivares and Damiano, 2007).

Field investigations that have attempted to correlate locally contractive (loose) soils with debris-flow initiation sites have obtained mixed results (Fleming et al., 1989; Anderson and Sitar, 1995; Gabet and Mudd, 2006; McKenna

* Corresponding author e-mail address*: mreid@usgs.gov*

et al., 2012). Although some sites were associated with contractive soil behavior, others were, at least initially, dilative. As sizeable slow-moving landslides advance downslope, their persistent deformation commonly creates areas of extension (stretching) and compression (shortening) within the slide mass (Baum and Fleming, 1991). Such behavior may thereby modify landslide bulk porosities in specific locations and make general characterizations difficult.

Here, we investigate the hypothesis that the dynamics of a slow-moving landslide can precondition regions of the slide to debris-flow initiation. In particular, we ask whether landslide extension with concomitant increases in material porosities can promote localized debris-flow mobilization from shallow secondary failures. To address this issue, we examine possible linkages between active slide movement and debris-flow initiation using greater than 20 years of displacement monitoring at the slow-moving Cleveland Corral landslide complex, California, USA (Fig. 1). We then use geotechnical testing and critical state soil mechanics to assess whether extensional and compressional regions within the slide complex create localized areas with materials that might contract upon shear failure and preferentially mobilize into debris flows.

2. Cleveland Corral Landslide and Debris-flow Characteristics

2.1. Landslide setting

The toe of the Cleveland Corral landslide complex is perched about 50 m above U.S. Highway 50 in the Sierra Nevada mountain range of California (Fig. 1). It is situated in a landslide-rich, 14 km-long highway corridor where more than 600 landslides have been mapped (Spittler and Wagner, 1998); this corridor follows the steep-walled, conifer-covered canyon of the South Fork of the American River. In this region, a strongly seasonal precipitation pattern exists, with most rainfall occurring November through March; summers are dry. The Cleveland Corral landslide complex has an elevation of approximately 1200 m, and snowfall is typically minimal and transient. Movement of most of the larger slides in this corridor, including the Cleveland Corral landslide, is episodic with reactivation of previously established failures. The landslides are dormant in the dry summer season and move only during a very wet winter and spring (with cumulative precipitation greater than the long-term annual average) – not every year. During exceptionally wet winter seasons, several of these slides have failed catastrophically and blocked the highway for multiple weeks (Kuehn and Bedrosian, 1987; Sydnor, 1997).

With a sinuous form about 450 m in length, the Cleveland Corral landslide complex consists of colluvium and older slide debris underlain by quartz mica schist and gneiss, near a contact with Cretaceous diorite (Spittler and Wagner, 1998). The colluvium is a clayey, silty sand containing 10-15% cobble-sized clasts of bedrock. The slide is a complex of mass movements; overall it is a series of contiguous earth slides (Cruden and Varnes, 1996) with internal scarps and toes, as well as secondary shallow slides and debris flows at the steeper lateral margins and toes of various earth slide components. Despite the overall extent of the slide, it is relatively thin with slip surfaces located in surficial materials above bedrock. Several shallow seismic surveys indicate a depth to bedrock of 5-10 m (Reid et al., 2003); shear rods we installed in the slide reveal active slip in different elements at depths of 3-5 m. Ground surface slopes vary between 10º and 30º, but locally steepen to over 40º.

2.2. Landslide movement

Following the catastrophic failure of the nearby (about 2 km upstream) Mill Creek landslide in 1997 that buried Highway 50 and temporarily dammed the South Fork of the American River (Sydnor, 1997), the U.S. Geological Survey (USGS) installed radio-telemetered real-time monitoring equipment on the Cleveland Corral landslide complex (Reid and LaHusen, 1998), which also has the potential to fail and bury the highway. Since 1997, current precipitation, movement, and groundwater conditions at the site have been available to the public (https://www.usgs.gov/natural-hazards/landslide-hazards/science/us-highway-50-california). In addition, we have performed annual, campaign-style, Global Positioning System (GPS) surveys of monuments located both on and off the slide. We used our own nearby GPS base station for static differential processing and obtained repeat year-to-year standard deviations of < 2 cm for stable monument positions. These survey data and associated notes on data collection and processing are available in a supporting USGS data release publication (Reid et al., 2019). Following wet seasons with landslide movement, we used kinematic GPS techniques to map recently active structural features visible on the ground surface.

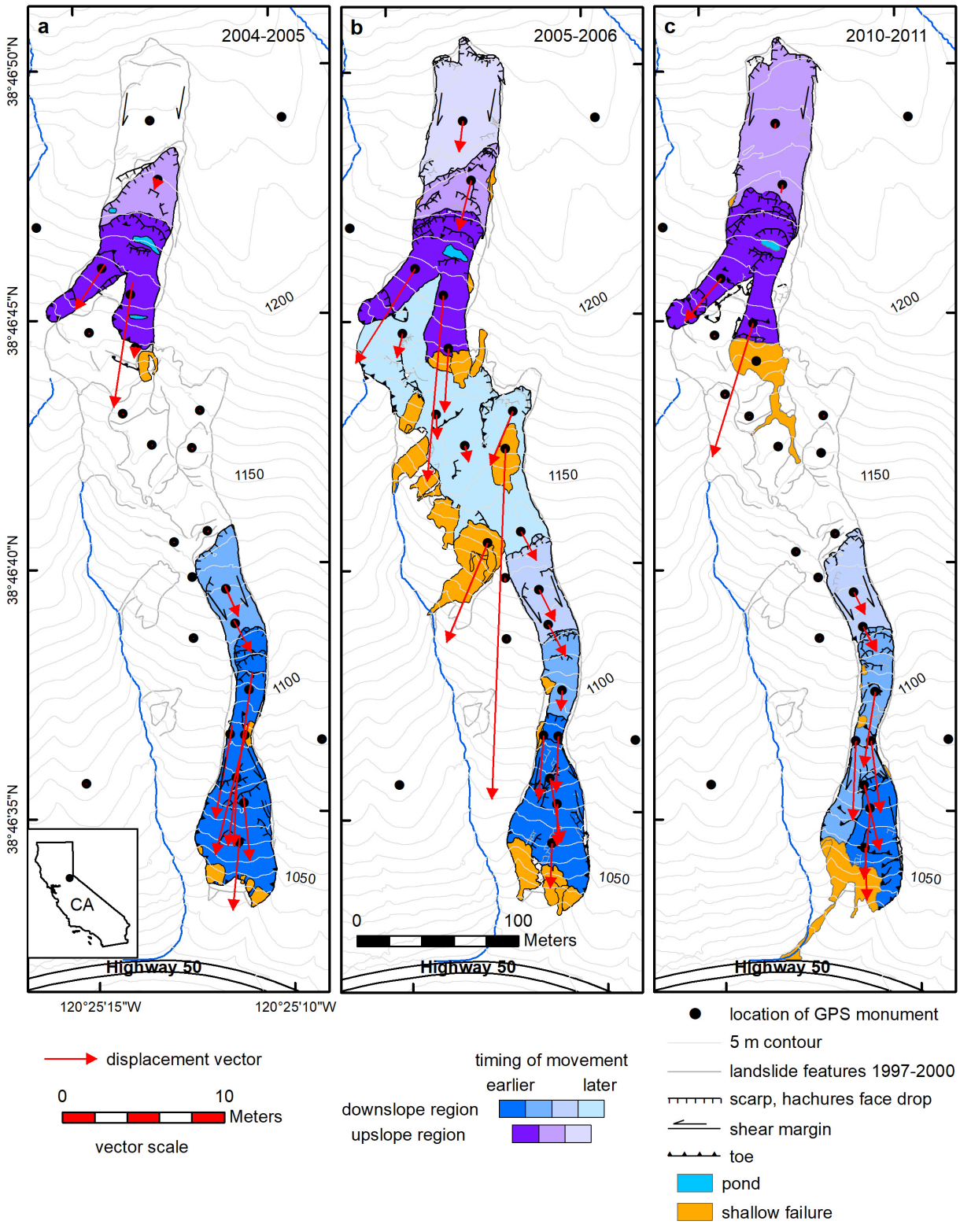

Fig. 1. Maps of the Cleveland Corral landslide complex showing active surface structures and kinematic elements during different wet years: (a) 2004-2005; (b) 2005-2006; (c) 2010-2011. Different elements are identified with different colors – blues for lower slide region, purples for upper. Elements with darker colors started moving earlier during the wet season, with movement typically progressing upslope into adjacent elements. Not all elements were active each year. Debris flows typically mobilized from shallow failures (orange) on the toes and margins of active elements. Displacement vector scale is 10X map scale.

Although the entire Cleveland Corral landslide complex has not failed catastrophically since our monitoring began in 1997, the combination of long-term real-time monitoring at specific locations with yearly overall displacement patterns has allowed us to correlate landslide movement with precipitation patterns. Various elements of the slide complex have moved during the wet seasons in 10 of the 21 years of monitoring. During the other years, all major slide elements remained dormant. Examples illustrating the differences in movement patterns for three water years when parts of the slide were active are shown in Figure 1. The slide complex consists of various kinematic elements that may move individually or in concert during a given wet year. In a wet season, certain elements typically move first – these include the overall toe (dark blue) and a mid-slide toe located in the upper section of the landslide (dark purple) (Fig. 1). Following initial movement, elements upslope and contiguous to the already moving elements may become active (lighter blues and purples), and additional activity may progress further upslope over several months. Depending on the wet season precipitation patterns, movement may be restricted to certain regions (Fig. 1a), although in a very wet season the entire slide complex can be active (Fig. 1b). When active, elements typically move at speeds of about 1-2 cm/day, but can range up to 20 cm/day. Even in active years, all elements cease motion by mid summer.

2.3. Debris-flow activity

Our monitoring has enabled us to identify conditions leading to debris-flow initiation from distinct parts of the overall slide complex. During above-average wet seasons, shallow (~0.5-1 m thick) debris slides (with typical volumes of about 5 to 400 m^3) often occur at the margins and toes of active elements. These shallow slides originate along new failure surfaces, either within transported material forming the larger slide complex or at the lateral scarps in adjacent, previously unfailed materials. Intense rainstorms trigger these shallow slides, and the larger of these features occur within active elements of the main slide, either at the toes or debutressed margins (primarily on the western margin of the complex) – moreover, the larger of these shallow failures often mobilize into debris flows (Fig. 1). Smaller and less mobile slides may also occur along locally steep lateral margins in adjacent materials. Interestingly, minimal shallow sliding generally occurs at the toes or margins of dormant elements, even during relatively intense rainstorms.

Due to prolonged slide movement, the toes of the active slide elements become oversteepened compared to typical overall slopes of the larger landslide elements (Fig. 2). Although this oversteepening should predispose a toe region to shallow secondary failures, most of these shallow failures occur when the larger, encompassing slide element is also actively moving downslope.

3. Testing Methodology

To examine the hypothesis that an active landslide can selectively dilate slide materials and thus promote subsequent debris-flow initiation, we undertook a two-pronged approach. We first performed geotechnical testing to define the critical state line using materials from within the larger landslide. We obtained samples both in bulk and in thin-walled brass tubes (6.4 cm diameter by 15.2 cm tall) pushed into the floor of a shallow excavation of the lower toe in 2008 (see Fig. 2 for sample location 022808). These samples were collected at a depth of 0.65 m, similar to the depth of typical shallow debris slides that have occurred at the toe of the slide complex. The materials were subsequently tested in the University of California, Berkeley GeoEngineering Laboratories using both consolidated undrained (CU) and consolidated drained (CD) triaxial methods with saturated samples under a range of confining stresses (32-120 kPa) that represent shallow conditions. The seven CU tests used moist tamped specimens prepared to different porosities that were subsequently sheared to critical state. Our three CD tests used *in situ* specimens extruded from the thin-walled tubes. For both types of tests, we computed critical state porosities at 12% axial strain representing sheared conditions. In our results (Fig. 3), we present the critical state line relating principal stress to material porosity, rather than void ratio, to allow ready comparison with field-derived porosity values.

We then performed field characterization to determine *in situ* landslide porosities in regions exhibiting local compressional (e.g. internal thrusts) or extensional (e.g. tension cracks) surfaces features, all within the toe area of the overall slide (see Fig. 2 for locations). We were interested in bulk porosities representative of regions (on the scale of small, shallow landslides) that could mobilize into debris flows. Conventional geotechnical tube samples, however, cannot fully capture the larger-scale effects of localized thrusting or cracking. We opted for a protocol capable of assessing the porosity of a larger sample using a ring-excavation method (Grossman and Reinsch, 2002). At each sample site, we excavated surface material to a depth of approximately 10-30 cm and then carefully pushed

or lightly tapped a 24.8 cm diameter stainless steel ring into the underlying slide material. We used a micrometer to measure the depth (relative to a small shelf placed across the upper edge of the steel ring) of the exposed material surface, collecting 33 depth measurements in a radial grid pattern. Then, we excavated and retained material from within the ring (typically 3000-4000 cm^3), and remeasured the post-excavation upper surface using the same grid pattern. From this, we could derive precise volumes for the excavated materials using radially weighted differences between surface measurements. The excavated materials were dried and weighed in the lab. Using dry weights and volumes, with a particle specific gravity of 2.7, we computed material porosities. We collected extensional samples (near surface tension cracks) during spring 2011, when the toe area had been recently active. Additional compressional samples (near thrusts) were collected in spring 2012, when the toe element was dormant.

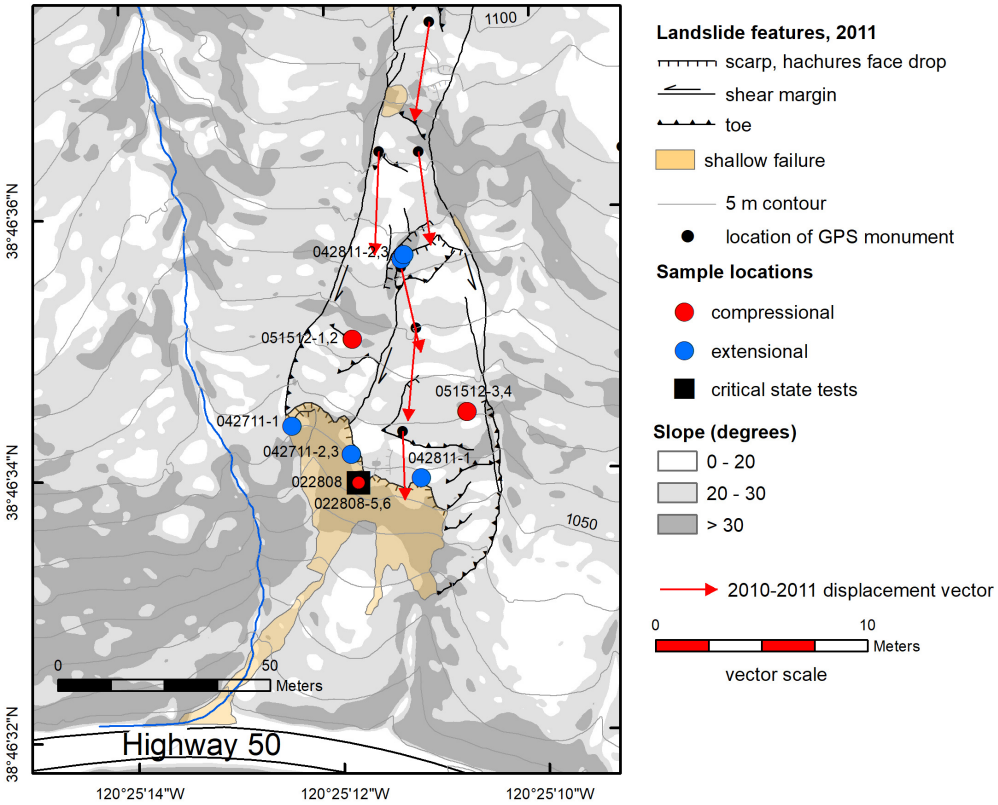

Fig. 2. *In situ* porosity locations at the toe of the Cleveland Corral landslide complex, categorized by nearby extensional or compressional surface structures. Surface structures shown as mapped during spring 2011; in some places, shallow failures mobilized into debris flows. Samples labeled with 022808 prefix were collected in 2008, prior to renewed activity in 2011. Vector displacement scale is 5X map scale.

4. Results

In Figure 3, we show our measured critical state line for toe landslide material using principal stress versus porosity during shear from both CU and CD triaxial tests. During our triaxial tests, materials with initial porosities higher (looser) than critical contracted during shear; those with initial porosities lower than critical (denser) dilated during shear. We also show *in situ* porosities determined by the ring-excavation method at different locations in the toe region (Fig. 2). For each location, we estimated likely *in situ* principal stress using sample depth, local slope, and saturated unit weight. Because sample depths were near the ground surface, we assumed that failure-appropriate principal stresses were oriented normal to the local ground slope.

The results for *in situ* porosities fall into three groups: looser than, near, and denser than the critical state line. The toe region is a complex of deforming landslide sub-elements with local surface expressions of extension (tension cracks) and compression (internal toes and thrusts) as shown in Figures 1 and 2. Sites with measured porosities greater (looser) than critical occurred near extensional features (Fig. 2), in particular these sites were located immediately upslope from the small headscarps of previous shallow slides. In preceding years, many of these

shallow slides mobilized into small debris flows (for examples, see Fig. 1). In contrast, sites with measured porosities lower (denser) than critical occurred near compressional features, in particular near the base of toes or just upslope of internal thrusts (Fig. 2). Nevertheless, some of these compressional sites, as well as several extensional sites had porosities near critical conditions for the given low principal-stress regime. Porosities near critical imply that minimal contraction or dilation would occur upon shearing; therefore, resultant pore-pressure increases or decreases that would enhance or impede motion would be less likely.

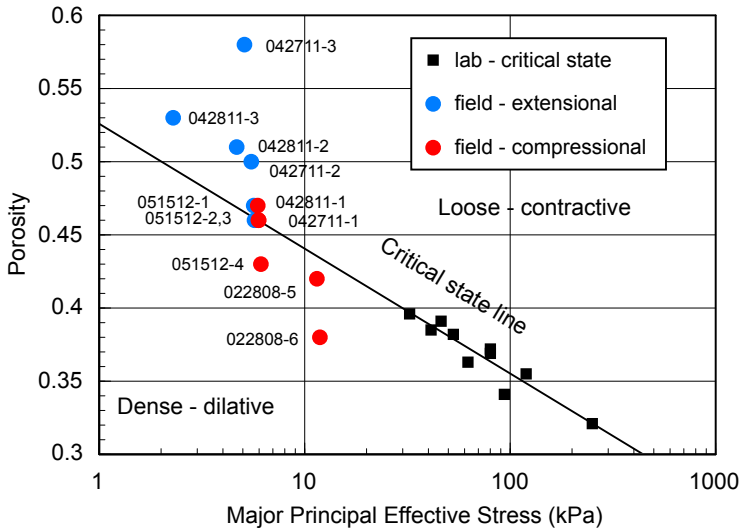

Fig. 3. Critical state line and *in situ* field porosities measured from the Cleveland Corral landslide complex toe region. Porosity values were collected near both extensional and compressional surface features. Materials looser than (above) the critical state line contract upon shearing and thus may aid liquefaction and reduce shear strength. Critical state line defined by CU and CD triaxial tests performed using low confining stresses readily achieved in the laboratory.

5. Concluding Discussion

Observations from 21 years of monitoring at the Cleveland Corral landslide complex indicated that debris flows mobilized from small, shallow, first-time failures on the topographically oversteepened toes and lateral margins during intense rainstorms (for examples, see Figs. 1 and 2). This association follows the precept that steep, wet ground promotes debris-flow mobilization from landslides (Iverson et al., 1997). However, not all shallow failures triggered during these rainstorms mobilized into flows – many small toe failures and those originating from scarps in adjacent areas on the lateral margins did not mobilize.

In addition to the spatial correlation with locally steep slopes, the largest shallow failures, with accompanying debris flows, occurred when encompassing kinematic elements of the Cleveland Corral landslide complex were actively moving downslope. This association implies that debris-flow mobilization from this slow-moving landslide complex required more than just steep and wet ground. Landslide movement can instigate spatial variations in stress patterns within slide materials, and thus may aid localized shallow failure. Our *in situ* porosity determinations indicated that looser materials occurred preferentially in regions of ground-surface extension, typically in the upper regions of steep active toes or lateral, debutressed margins. These extensional regions resulted from dynamic slide movement and therefore could vary over time. Loose materials have the propensity to contract upon shear, generate elevated pore-water pressures, promote widespread liquefaction beyond an initial shear surface, and thereby potentially facilitate debris-flow mobilization.

Active slide motion can promote debris-flow initiation through several processes – oversteepening of toes and lateral margins, as well as stretching or extending materials (to an overall condition looser than critical state) within the slide. The topographic oversteepening promotes shallow failures, whereas the extension produces materials that can contract upon shear failure and thereby promote material liquefaction. These combined processes create select areas that are prone to debris-flow mobilization during intense rainstorms, even as the overall larger landslide maintains slow movement.

Acknowledgements

Monitoring of the Cleveland Corral landslide complex was conducted in cooperation with the Eldorado National Forest. Richard LaHusen (USGS) was instrumental in developing the real-time monitoring system deployed at the slide. We thank Michael Riemer (University of California, Berkeley) for performing the laboratory triaxial testing and Charlotte Wirion for field assistance in obtaining *in situ* porosities. Brian Collins (USGS), Nancy Calhoun (Oregon Department of Geology and Mineral Industries), and an anonymous reviewer helped improve the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Anderson, S.A. and Sitar, N., 1995, Analysis of rainfall-induced debris flows, Journal of Geotechnical Engineering, v. 121, no. 7, p. 544-552, doi: 10.1061/(ASCE)0733-9410(1995)121:7(544).

Baum, R.L. and Fleming, R.W., 1991, Use of longitudinal strain in identifyng driving and resisting elements of landslides, Geological Society of America Bulletin, v. 103, no. 8, p. 1121-1132.

Berti, M., and Simoni, A., 2005, Experimental evidences and numerical modelling of debris flow initiated by channel runoff, Landslides, v. 2, p. 171-182, doi: 10.1007/s10346-005-0062-4.

Cannon, S.H., Kirkham, R.M., and Parise, M., 2001, Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado, Geomorphology, v. 39, p. 171-188, doi: 10.1016/S0169-555X(00)00108-2.

Coe, J.A., Kinner, D.A., and Godt, J.W., 2008, Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado, Geomorphology, v. 96, p. 270-297, doi: 10.1016/j.geomorph.2007.03.017.

Crosta, G.B. and Frattini, P., 2008, Rainfall-induced landslides and debris flows, Hydrological Processes, v. 22, no. 4, p. 473-477.

Cruden, D.M. and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Schuster, R.L., eds., Landslides: Investigation and Mitigation, Volume Special Report 247: Washington, D. C., Transportation Research Board, p. 36-75.

Fleming, R.W., Ellen, S.D., and Algus, M.A., 1989, Transformation of dilative and contractive landslide debris into debris flows - an example from Marin County, California, Engineering Geology, v. 27, p. 201-223.

Gabet, E.J. and Mudd, S.M., 2006, The mobilization of debris flows from shallow landslides, Geomorphology, v. 74, p. 207-218, doi: 10.1016/j.geomorph.2005.08.013.

Geertsema, M., Clague, J.J., Schwab, J.W., and Evans, S.G., 2006, An overview of recent large catastrophic landslides in northern British Columbia, Canada, Engineering Geology, v. 83, p. 120-143, doi: 10.1016/j.enggeo.2005.06.028.

Grossman, R.B. and Reinsch, T.G., 2002, Bulk density and linear extensibility, *in* Dane, J. H., and Topp, G. C., eds., Methods for Soil Analysis, Part 4, Physical Methods: Madison, Wisconsin, Soil Society of America, p. 201-228.

Houlsby, G.T., 1991, How the dilatancy of soils affects their behaviour, Proceedings of the Tenth European Conference on Soil Mechanics and Foundation Engineering, Florence, v. 4, p. 1189-1202.

Hungr, O., Morgan, G.C., and Kellerhals, R., 1984, Quantitative analysis of debris torrent hazards for design of remedial measures, Canadian Geotechnical Journal, v. 21, no. 4, p. 663-677.

Iverson, R.M., Reid, M.E., and LaHusen, R.G., 1997, Debris-flow mobilization from landslides, Annual Review of Earth and Planetary Sciences, v. 25, p. 85-138, doi: 10.1146/annurev.earth.25.1.85.

Iverson, R.M., Reid, M.E., Iverson, N.R., LaHusen, R.G., Logan, M., Mann, J.E., and Brien, D.L., 2000, Acute sensitivity of landslide rates to initial soil porosity, Science, v. 290, no. 5491, p. 513-516, doi: 10.1126/science.290.5491.513.

Jibson, R.W., 2005, Landslide hazards at La Conchita, California: U.S. Geological Survey, Open-File Report 2005-1067, 12 p.

Kuehn, M.H. and Bedrosian, T.L., 1987, 1983 U.S. Highway 50 Landslide near Whitehall, El Dorado County, California, California Geology, v. 40, no. 11, p. 247-255.

Malet, J.-P., Maquaire, O., Locat, J., and Remaître, A., 2004, Assessing debris flow hazards associated with slow moving landslides: methodology and numerical analyses, Landslides, v. 1, p. 83-90, doi: 10.1007/s10346-003-0005-x.

Malet, J.-P., Laigle, D., Remaître, A., and Maquaire, O., 2005, Triggering conditions and mobility of debris flows associated to complex earthflows, Geomorphology, v. 66, p. 215-235, doi: 10.1016/j.geomorph.2004.09.014.

McKenna, J.P., Santi, P.M., Amblard, X., and Negri, J., 2012, Effects of soil-engineering properties on the failure mode of shallow landslides, Landslides, v. 9, p. 215-228, doi: 10.1007/s10346-011-0295-3.

Morton, D.M. and Campbell, R.H., 1974, Spring mudflows at Wrightwood, Southern California, Quarterly Journal of Engineering Geology, v. 7, no. 4, p. 377-384.

Okura, Y., Kitahara, H., Ochiai, H., Sammori, T., and Kawanami, A., 2002, Landslide fluidization process by flume experiments, Engineering Geology, v. 66, no. 1-2, p. 65-78, doi: 10.1016/S0013-7952(02)00032-7.

Olivares, L. and Damiano, E., 2007, Postfailure mechanics of landslides: Laboratory investigation of flowslides in pyroclastic soils, Journal of Geotechnical and Geoenvironmental Engineering, v. 133, no. 1, p. 51-62, doi: 10.1061/ ASCE 1090-0241 2007 133:1 51.

Reid, M.E. and LaHusen, R.L., 1998, Real-time monitoring of active landsides along Highway 50, El Dorado County, California Geology, v. 51, no. 3, p. 17-20.

Reid, M.E., Brien, D.L., LaHusen, R.L., Roering, J.J., de la Fuente, J., and Ellen, S.D., 2003, Debris-flow initiation from large slow-moving landslides, *in* Rickenmann, D., and Chen, C., eds., Mechanics, Prediction and Assessment: Proc. of the Third International DFHM Conference, Davos, Switzerland: Rotterdam, Millpress Science Publishers, p. 155-166.

Reid, M.E., Brien, D.L., and Roering, J.J., 2019, Survey monument positions for the Cleveland Corral landslide near U.S. Highway 50, El Dorado County, California, U.S. Geological Survey data release, doi: 10.5066/P9X62EV3.

Schofield, A.N. and Wroth, C.P., 1968, Critical State Soil Mechanics: New York, McGraw-Hill, 218 p.

Spittler, T.E. and Wagner, D.L., 1998, Geology and slope stability along Highway 50, California Geology, v. 51, no. 3, p. 3-14.

Sydnor, R.H., 1997, Reconnaissance engineering geology of the Mill Creek Landslide of January 24, 1997, California Geology, v. 50, no. 3, p. 74-83.
Takahashi, T., 1991, Debris Flow: Rotterdam, A. A. Balkema, IAHR Monograph, 165 p.
Wood, D.M., 1990, Soil Behavior and Critical State Mechanics: Cambridge, UK, Cambridge Universtiy Press, 462 p.