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Landslide mobility and hazards: implications of the 2014 Oso disaster

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ABSTRACT

Landslides reflect landscape instability that evolves over meteorological and geological timescales, and they also pose threats to people, property, and the environment. The severity of these threats depends largely on landslide speed and travel distance, which are collectively described as landslide "mobility". To investigate causes and effects of mobility, we focus on a disastrous landslide that occurred on 22 March 2014 near Oso, Washington, USA, following a long period of abnormally wet weather. The landslide's impacts were severe because its mobility exceeded that of prior historical landslides at the site, and also exceeded that of comparable landslides elsewhere. The $\sim 8 \times 10^6$ m^3 landslide originated on a gently sloping ($<20°$) riverside bluff only 180 m high, yet it traveled across the entire $\sim$1 km breadth of the adjacent floodplain and spread laterally a similar distance. Seismological evidence indicates that high-speed, flowing motion of the landslide began after about 50 s of preliminary slope movement, and observational evidence supports the hypothesis that the high mobility of the landslide resulted from liquefaction of water-saturated sediment at its base. Numerical simulation of the event using a newly developed model indicates that liquefaction and high mobility can be attributed to compression- and/or shear-induced sediment contraction that was strongly dependent on initial conditions. An alternative numerical simulation indicates that the landslide would have been far less mobile if its initial porosity and water content had been only slightly lower. Sensitive dependence of landslide mobility on initial conditions has broad implications for assessment of landslide hazards.

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1. Introduction

Landslide mobility has long intrigued earth and planetary scientists (Legros, 2002). The vexing nature and practical significance of the phenomenon were first recognized in 1881, when much of the town of Elm, Switzerland, was buried by a landslide involving about 10^7 m^3 of material that traversed a path 2017 m in length (L) as it descended from a maximum height (H) of 613 m (Hsu, 1978). The Elm disaster motivated development of a landslide mobility index known as the fahrböschung (Heim, 1882, 1932), or more commonly, as the H/L ratio (Corominas, 1996). The Elm landslide had $H/L \approx 0.3$, and $H/L < 0.6$ was once thought to be indicative of anomalously low intrinsic friction exhibited by many landslides with volumes greater than about 10^6 m^3 (Scheidegger, 1973). Recent field, laboratory and theoretical investigations have largely discredited this notion, in part because H/L is an inadequate measure of bulk frictional resistance (e.g., Corominas, 1996; Iverson, 1997; Dade and Huppert, 1998; Legros, 2002; Iverson et al., 2011; Farin et al., 2014). Nevertheless, H/L values (or their reciprocals, L/H values) serve an important practical purpose be-

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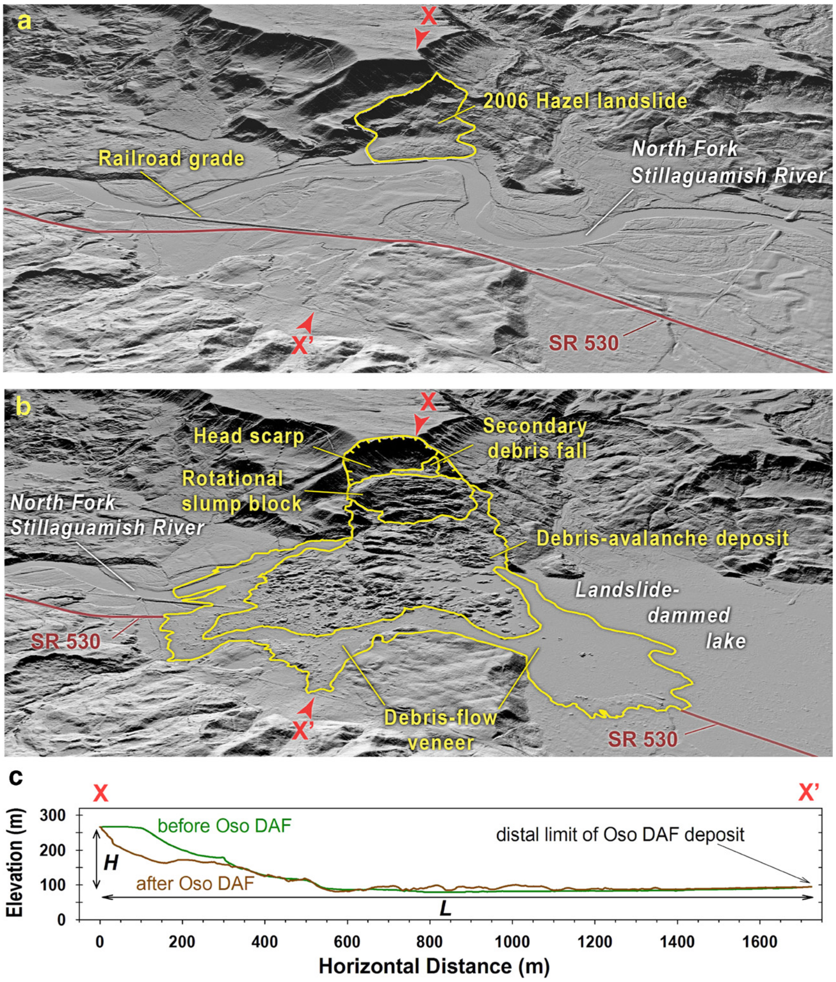

Fig. 1. Shaded relief lidar images and longitudinal topographic profiles of the Oso DAF site. a and b: Northwest-looking oblique perspectives of major geomorphic and cultural features visible in 2013 and 2014 lidar imagery acquired before and after the Oso DAF occurred. The DAF encompasses the entire area enclosed by the outer yellow line in b. c: Longitudinal topographic profiles and definitions of H and L along the transect $X-X'$ shown in a and b. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cause they identify locations that can be overrun by a landslide with a specific source area and sufficiently large L/H value.

A landslide near Oso, Washington, USA, on 22 March 2014 had a volume of about 8×10^6 m^3, similar to that of the Elm landslide of 1881, but its mobility (as gauged by $H/L = 0.105$ or $L/H = 9.5$) was nearly three times greater. As a consequence of its high mobility, the landslide crossed the entire 1-km-wide floodplain of the North Fork Stillaguamish River (Fig. 1 and Supplementary Figs. 1 and 2). As it overran the floodplain it demolished a neighborhood, buried highway SR 530, and caused 43 fatalities, ranking it second to only a 1985 event in Mameyes, Puerto Rico, as the worst landslide disaster in U.S. history (cf. Jibson, 1992). Owing to its high mobility and the character of its variegated deposits, we describe the landslide at Oso as a debris avalanche-flow (DAF) (cf. Hungr et al., 2014). An alternative descriptive term, widely used in geotechnical engineering, is flowslide (Mitchell and Markell, 1974; Dawson et al., 1998).

The Oso DAF (officially named the SR 530 Landslide by Washington State) originated on a slope that was only 180 m high and inclined $<20°$, on average (Fig. 1c). The same slope had failed repeatedly in the past, most recently in 2006, when a landslide partially dammed the river and caused minor flooding. However, the 2006 landslide (known locally as either the Hazel or Steelhead landslide) and other historical landslides on the slope had not exhibited exceptional mobility (Fig. 1a). Elsewhere, landslides that transform into mobile, high-speed flows almost invariably begin on slopes $>20°$, and initiation sites steeper than 30° are typical (Voight, 1978; Iverson et al., 1997). The great mobility of the Oso DAF therefore poses an important scientific problem. In this paper we aim to provide improved understanding of the Oso DAF and also to address broader issues concerning the mechanics of long-runout landslides and their implications for landslide hazard evaluation.

1.1. Meteorological and geological context

The Oso DAF occurred on a dry, sunny day, but it followed a long period of unusually heavy precipitation in the area. Well-established hydromechanical principles explain why most landslides occur when weather has been wet, giving rise to high groundwater pressures (Lu and Godt, 2013). Analysis of data from a nearby weather station with an 86-year record indicates that the 45 days preceding the Oso DAF had been wetter than 98.2% of 45-day periods in the past (Table 1). Moreover, the 180 days preceding the landslide had been wetter than 91% of similar periods in the past, and the four-year period that concluded on 31 March 2014 was the wettest such four-year period on record. Linear theory that relates rain infiltration rates to changes in groundwater pressure explains why the timescale for landslide onset can differ by weeks, months, or even years from the timescale of triggering rainfall (Iverson, 2000). However, as a result of the effects of hydrological nonlinearities and geological heterogeneities, quantitative

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