Geomorphology 141-142 (2012) 88–98

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Evidence for earthquake triggering of large landslides in coastal Oregon, USA

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ARTICLE INFO

Article history:
Received 2 September 2011
Received in revised form 9 December 2011
Accepted 12 December 2011
Available online 19 December 2011

Keywords:
Landslide
Earthquake
Coastal bluff
Oregon
Tsunami
Cascadia subduction zone

ABSTRACT

Landslides are ubiquitous along the Oregon coast. Many are large, deep slides in sedimentary rock and are dormant or active only during the rainy season. Morphology, observed movement rates, and total movement suggest that many are at least several hundreds of years old. The offshore Cascadia subduction zone produces great earthquakes every 300–500 years that generate tsunami that inundate the coast within minutes. Many slides and slide-prone areas underlie tsunami evacuation and emergency response routes. We evaluated the likelihood of existing and future large rockslides being triggered by pore-water pressure increase or earthquake-induced ground motion using field observations and modeling of three typical slides. Monitoring for 2–9 years indicated that the rockslides reactivate when pore pressures exceed readily identifiable levels. Measurements of total movement and observed movement rates suggest that two of the rockslides are 296–336 years old (the third could not be dated). The most recent great Cascadia earthquake was M 9.0 and occurred during January 1700, while regional climatological conditions have been stable for at least the past 600 years. Hence, the estimated ages of the slides support earthquake ground motion as their triggering mechanism. Limit-equilibrium slope-stability modeling suggests that increased pore-water pressures could not trigger formation of the observed slides, even when accompanied by progressive strength loss. Modeling suggests that ground accelerations comparable to those recorded at geologically similar sites during the M 9.0, 11 March 2011 Japan Trench subduction-zone earthquake would trigger formation of the rockslides. Displacement modeling following the Newmark approach suggests that the rockslides would move only centimeters upon coseismic formation; however, coseismic reactivation of existing rockslides would involve meters of displacement. Our findings provide better understanding of the dynamic coastal bluff environment and hazards from future subduction-zone earthquakes.

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1. Introduction

Many large, deep, sporadically active or dormant rockslides occur along the Pacific coastline of Oregon (North and Byrne, 1965; Burns et al., 2011). Renewed, primarily slow movement (generally centimeters/week) of the sporadically active slides occurs during most rainy seasons following prolonged, intense rainfall (e.g., Schlicker et al., 1973). Their slow movement keeps pace with coastal bluff retreat; hence, their observed effects on coastal geomorphology are largely limited to progressive disruption of the marine terrace they occupy. The slides do not generally present extreme hazard to human safety because they move slowly; but they do destroy roadways, infrastructure, and homes and render U.S. Highway 101 (the Pacific Coast Highway) unusable at times causing economic hardship to coastal communities that rely on tourism for financial support. Although these rockslides are relatively innocuous compared to more rapidly moving slides, their potential reactivation and initiation of similar rockslides during a future earthquake could create significant hazards to human safety. Great earthquakes along the Cascadia subduction zone located offshore will occur in the future and cause considerable ground shaking that destroys buildings and infrastructure (Heaton and Hartzell, 1987; Clague, 1997). Paleoseismic studies suggest that these earthquakes recur every 300–500 years (e.g., Atwater and Hemphill-Haley, 1997; Kelsey et al., 2002, 2005; Nelson et al., 2004) and the last such earthquake occurred on 26 January 1700 with an estimated magnitude of 9.0 (Satake et al., 1996). Subduction-zone earthquakes may generate large tsunami that will reach the coastline within tens of minutes and cause widespread devastation (Priest, 1995), similar to the recent tragic illustrations from the great 2011 Japan and 2004 Sumatra earthquakes; the 1700 earthquake off the Oregon coast produced a tsunami that inundated coastal areas as high as 10–12 m above mean sea level (amsl) (Goldfinger et al., 2003; Geist, 2005). Coastal rockslides may experience substantial renewed movement during an earthquake and new rockslides may form. These rockslides may render tsunami evacuation and

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0169-555X/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.geomorph.2011.12.026

emergency response routes unusable, potentially endangering the lives of many more people than currently anticipated.

To evaluate potential initiation mechanisms of large rockslides in coastal Oregon and seismogenic movement of existing slides, we studied three rockslides typical of the central coast (Fig. 1). Our studies included surface and subsurface characterization of the rockslides and monitoring of movement and hydrologic conditions related to their wet-season reactivation. Our results and inferred conditions at the time of rockslide formation were used in limit-equilibrium slope-stability analyses to evaluate potential initiation by increased pore-water pressures or earthquake ground shaking. Finally, we evaluated potential coseismic displacement of newly formed and reactivated rockslides following the Newmark (1965) approach. Our findings may be useful for regional hazard and risk assessments, as well as for increasing our understanding of processes that sculpt the dynamic coastal bluff environment in central Oregon. Additionally, the methods utilized herein could be useful for evaluating potential initiation mechanisms of other landslides. Jibson and Keefer (1993) demonstrated the utility of similar methods for evaluating potential triggering mechanisms for landslides in the New Madrid, USA seismic zone. Hence, these approaches also may be followed to estimate the relative contribution of earthquake-triggered landsliding to geomorphic evolution at multiple temporal and spatial scales.

2. Geologic setting

The Oregon coastal region (Fig. 1) is located upon the North American tectonic plate about 90 km east from where it overrides the Juan de Fuca plate forming the Cascadia subduction zone offshore (e.g., Clague, 1997). The rockslides we studied (Carmel Knoll, Devils Punchbowl, and Johnson Creek) occur mostly in carbonaceous and micaceous mudstone, siltstone, and sandstone of the middle Miocene Astoria Formation (North and Byrne, 1965; Schlicker et al., 1973; Priest and Allan, 2004), which has an approximate shear-wave velocity (V_s) of 613 m/s (Madin and Wang, 1999). Along the coast, the Astoria Formation strikes about north–south and dips ~10–30° west; however, the unit is mostly massive with poorly defined bedding and stratigraphic facies variation in the vicinity of the rockslides, being comprised mostly of clayey, sandy siltstone. Rugged basalt headlands also occur along the coastline; their much greater resistance to wave erosion relative to the sedimentary units has resulted in formation of numerous embayments typically several kilometers in along-shore length. The sedimentary rock units are uplifted and their upper surfaces are generally nearly flat, having been eroded into a series of marine terraces (Schlicker et al., 1973). Flat-lying Quaternary marine terrace sands generally a few meters thick cap most of the rock, forming a relatively flat ground surface that typically slopes only about 1° toward the coastline. These terrace sands can be very similar to parts of the Astoria Formation (Schlicker et al., 1973).

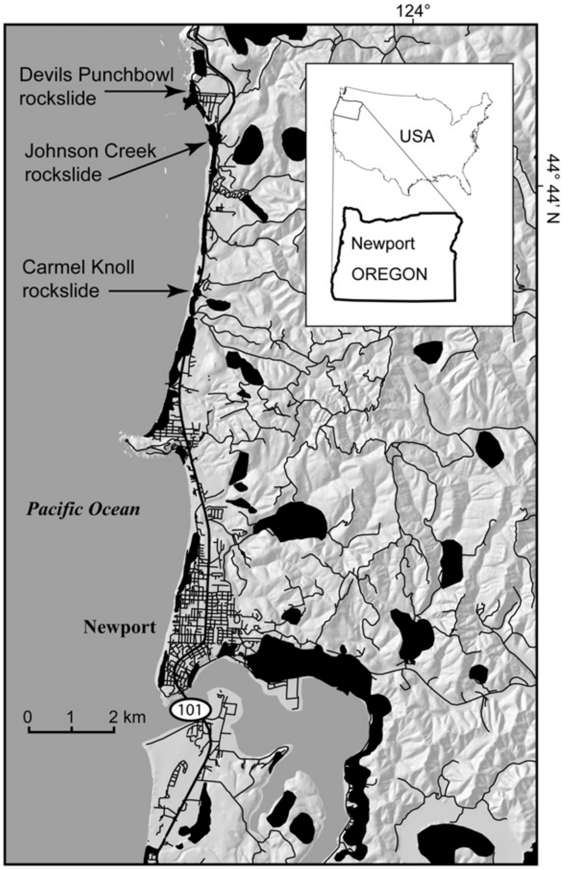

Fig. 1. Map showing location of study. Landslides mapped previously (Burns et al., 2011) are in black and the rockslides evaluated during this study are noted. Black lines indicate roadways.

Uplift of the rock and terrace sands and action of ocean waves has resulted in formation of bluffs typically 35–45 m high. In the three rockslide areas, bluffs retreat at rates of 0.15–0.24 m/y (Priest and Allan, 2004). The bluffs are sloped ~60°–90° where they are presently stable. However, landslides are pervasive (e.g., Schlicker et al., 1973; Gentile, 1978). Nearly all bluffs are fronted by persistent shallow landslides (few meters thick). Much larger rockslides and rockslide deposits that extend as much as hundreds of meters landward occur sporadically (Fig. 1). These are thick (tens of meters) with gently sloping basal failure surfaces occurring in the sedimentary bedrock near and below sea level. Landslides and landslide deposits also are widespread in the nearby Coast Range mountains. Priest and Allan (2004) identified 216 landslides primarily along the shoreline in northern Lincoln County (location of our study) and Burns et al. (2011) mapped the boundaries of 773 landslides in the entire county; these landslides cover 12.2% of its area. Additionally, Burns et al. (2011) documented the locations of 889 historical landslides in the county; an unknown number of these correlate with the 773 landslides whose boundaries were mapped.

Landslide activity is most extensive during the rainy months of October–March (North and Byrne, 1965; Schlicker et al., 1973) when about 78% of the 1.72 m of annual rainfall occurs (based on records from 1893 to 2010 for Newport weather station 356032; WRCC, 2011). Infiltration of rainwater results in elevated pore-water pressures that reduce effective stresses and, consequently, frictional strength of slope materials, which results in landslide reactivation. The large, seasonally active rockslides that occur in the sedimentary rock units typically move a few centimeters to a few decimeters each year. Many of these seasonally active rockslides are smaller reactivations of much larger but presently dormant rockslides (Gentile, 1978; Priest and Allan, 2004). Historical formation of the large rockslides outside of larger dormant rockslides is apparently very rare, and the ages of the rockslides we studied are unknown. However, U.S. Highway 101 has been damaged by movement of the Carmel Knoll and Johnson Creek rockslides since its construction during the 1940s (Oregon Department of Transportation and Geotechnical Group, 1986; Priest et al., 2006); thus these rockslides formed prior to highway completion during 1943. The apparent prehistoric formation of so many large rockslides and their large total displacements (tens of meters) relative to small annual displacements caused some to surmise that they were formed during a wetter climatic cycle or during earthquake ground shaking (Komar, 2004; Priest and Allan, 2004). Several studies have found that regional climatic conditions have been steady for at least the past 600 years (Keen, 1937; Graumlich, 1987; Worona and Whitlock, 1995; Gedalof and Smith, 2001). Most relevant to the present study, Graumlich (1987) estimated annual precipitation for the region for the 300-year period