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Multimodal method for coseismic landslide hazard assessment

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ABSTRACT

Regional-scale coseismic landslide hazard assessments have traditionally been based on infinite-slope analyses, considering only a single mode of failure. Inventories and landslide reconnaissance work have shown a diverse range of coseismic landslide modes with significantly different consequences of failure. This paper presents a multimodal approach for regional-scale coseismic landslide hazard assessment. Through a two-step procedure, the multimodal method explicitly accounts for four general landslide types commonly observed during earthquakes: rock-slope failures, disrupted soil slides, coherent rotational slides, and lateral spreads. First, the susceptibility to each landslide mode is evaluated based on topography. Second, coseismic landslide hazards are assessed using mode-specific geotechnical models. A trial multimodal landslide assessment is presented for the seismically active country of Lebanon. Results show that the computed coseismic landslide hazard closely matches field-verified slope activity across different regions of the country exhibiting a range of failure modes. These results qualitatively demonstrate the efficacy of the procedure and suggest that multimodal coseismic landslide hazard analysis is especially well-suited for regions with varying terrain and where landslide inventories are not available.

1. Introduction

Earthquake-induced, or *coseismic*, landslides occur in great number during moderate to large (M > 5) earthquakes (Keefer, 2013; Rodrıguez et al., 1999). These landslides typically occur across regions spanning hundreds to thousands of square kilometers (Keefer, 1984). The widespread geographic distribution of coseismic landslides makes them, by definition, regional-scale events. For this reason, coseismic landslide hazards are usually assessed using regional-scale (i.e., 1:250,000–1:25,000, Corominas et al., 2014) forecasting models. These models are valuable because they indicate the spatial distribution of coseismic landslides and additionally have the potential to capture seismic performance and propagation of risk across a region. This is especially important when considering the effects of slope failures on geographically distributed critical infrastructure systems, which are highly vulnerable to coseismic landslides (e.g. Wartman et al., 2003).

Regional-scale coseismic landslide hazard assessments are typically based on infinite-slope analyses (e.g. Wieczorek et al., 1985; Khazai and Sitar, 2000; Jibson et al., 2000; Saygili and Rathje, 2008), which theoretically limit their applicability to shallow landslides (Corominas et al., 2014). While infinite-slope based models have been shown to perform adequately for events where landslides primarily consist of shallow disrupted soil slides (e.g. the 1994 Northridge earthquake, Dreyfus et al., 2013), post-earthquake field investigations of other earthquakes reveal a diverse styles of coseismic landslides including rock-slope failures, rotational slumps, and lateral spreads (e.g. Keefer, 1984; Rodrıguez et al., 1999; Sitar and Khazai, 2001; Bommer and Rodŕıguez, 2002; Keefer, 2002; Dai et al., 2011; Wartman et al., 2013). Ideally, landslide hazard assessments should capture the full range of coseismic failure modes.

In this paper, we present a regional-scale coseismic landslide hazard assessment method that explicitly accounts for different modes of failure. This *multimodal* method considers four general modes (or types) of landslides commonly observed during earthquakes: (1) rock-slope failures, (2) disrupted soil slides, (3) coherent rotational slides, and (4) lateral spreads. Application of the multimodal method follows a two-step procedure: first, susceptibility to each landslide mode is evaluated based on topography; then, coseismic landslide hazards are assessed using mode-specific geotechnical models. We developed the multimodal approach for regions where inventories of coseismic landslides are incomplete or otherwise not available. In such regions, it is often possible to estimate geologic strength parameters and acquire digital elevation model (DEM) data, but impractical to apply regression-based assessment procedures trained on coseismic landslide databases from a specific geographic area (e.g. Lee et al., 2008).

We conduct a trial multimodal landslide hazard assessment for Lebanon, which has good quality geologic and topographic data. The discovery and mapping of the offshore Mount Lebanon Thrust Fault (Elias

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et al., 2007), linked to a historic ~M7.2 earthquake, has significantly raised the seismic hazard in Lebanon (Huijer, 2010; Huijer et al., 2011) and suggests the potential for coseismic landslides across the country. Results from our trial application show that the computed coseismic landslide hazard closely matches field-verified slope activity across different regions of the country exhibiting widely varied terrains. The results demonstrate the efficacy of the procedure and suggest that multimodal coseismic landslide hazard analysis is well suited for regions of varied terrain where landslide inventories are not available. A unique benefit of the multimodal method is that it provides a spatial disaggregation of coseismic landslide mode across a region, which offers a cursory assessment of risk since each landslide failure mode will have different impacts on human populations and different consequences for infrastructure systems and the built environment.

1.1. Coseismic landslide types and consequences

Keefer (1984) identified fourteen commonly occurring coseismic landslide modes of failure, which were simplified and refined in later work to three main categories: disrupted slides, coherent landslides, and lateral spreads and flows (Keefer, 1999). This range of coseismic failure modes has been reported in many post-event landslide investigations. For example, Keefer (2000) mapped ~1300 coseismic landslides within a 2,000 km^2 zone that was highly impacted by the 1989 M6.9 Loma Prieta, California earthquake. Keefer (2000) observed that while most landslides were disrupted a considerable fraction (26%) classified as coherent failures. Similarly, Khazai and Sitar (2004) found a majority of the landslides initiated by the 1999 M7.6 Chi-Chi, Taiwan earthquake to be disrupted failures, with coherent (11%) and "other" (4%) types of landslides also being significant (lateral spreads were omitted from the Loma Prieta and Chi-Chi datasets.) Wartman et al. (2013) mapped coseismic landslides triggered by the 2011 M9.0 Tohoku earthquake across a 28,000 km^2 region and found most landslides to be disrupted (63%), with a lesser but significant fraction to be lateral spreads (34%) and coherent failures (3%). However, taken in the context of "sediment mobilization" or landslide erosion volume, lateral spreads were the dominant mode of coseismic landslides (Wartman et al., 2013). Unlike disrupted failures, lateral spreads are not captured by traditional infinite-slope based landslide hazard analyses.

Coseismic landslide failure modes are each associated with unique consequences of failure (e.g. Wartman et al., 2013; Keefer, 2013). For example, during the 2010–2011 Canterbury, New Zealand earthquake sequence, widespread liquefaction and associated lateral spreading resulted in significant damage to buildings and infrastructure systems (economic losses of ~$15B NZD, Cubrinovski et al., 2014) but did not cause human losses. In contrast, rock-slope failures, which occurred in many locations in the Christchurch region, resulted in both highly localized damage and significant loss-of-life (Massey et al., 2012).

2. Multimodal model development

The multimodal method was developed to assess susceptibility to four common types of landslides and to compute the mode-specific coseismic landslide hazard on a regional scale. Topographic slope was adopted as an indicator to determine terrain susceptible to landslides, and where indicated, the landslide mode(s) most likely to occur. A geospatially continuous mode-specific model was used to compute potential coseismic displacements based on the local ground shaking intensity. The coseismic landslide hazard was then defined based on computed displacements for all modes of failure following previous landslide studies (e.g. Godt et al., 2008; Jibson and Michael, 2009) and recognizing that coseismic displacement ultimately governs the serviceability of a slope after an earthquake (Kramer, 1996). The following sections describe the procedure used to identify landslide susceptibility and the geotechnical models used to assess each landslide mode.

2.1. Types of landslides

Keefer (1984) studied 40 coseismic landslide datasets and found several types of landslides to be "very abundant" or "abundant," including rock falls and slides, disrupted soil slides, soil slumps, and soil lateral spreads. To capture this variation in coseismic landslide type, we focused on four fundamental modes of failure. Referencing Keefer's (1984) coseismic landslide classification system, these are: (1) rock slides and falls, (2) disrupted soil slides, (3) coherent rotational slides (i.e., soil and rock slumps), and (4) lateral spreads (Fig. 1). Table 1 summarizes the landslide modes, as well their commonly observed characteristics and typical source zone slope inclinations. Fig. 2 shows an example of each type of landslide. Other less common modes of failure, such as soil falls or earth flows, were omitted as they are unlikely to contribute significantly to the overall landslide hazard.

2.1.1. Mode of failure susceptibility zonation

For many landslide susceptible regions in the world, detailed inventories are not available, thus preventing the use of region-specific statistical measures of future landslide susceptibility. However, previous studies and landslide reconnaissance investigations have identified clear relationships between mode of failure and slope of landslide source areas (e.g. Keefer, 1984; Keefer, 2013). We adopted these findings to delineate the most likely coseismic mode(s) of failure within a study region within specific slope bounds. Lateral spread susceptibility was restricted to slopes of 0°–6° based on Bartlett and Youd (1995) who found that liquefaction in slopes > 6° would likely produce flow slides, which are not considered in this work. Slopes from 15°–50° are assumed to be susceptible to disrupted soil sliding based on observations of Keefer (1984) and the assumption that slopes steeper than 50° exhibit rock-like behavior.

Terrain susceptible to potentially significant coherent rotational sliding movements was limited to slopes from 20° to 35°. While coseismic rock and soil rotational slides failures have been observed in gentler slopes in past events, we constrained failures based on our assumed slip surface geometry (Section 2.2.3) and an assumed transition from deep to shallow soil and rock failures above 35° slopes. Rock-slope failures were considered for only slopes steeper than 35° based on the observations of Toppe (1987); Lee (2013), and Keefer (2013).

Slopes from 6° to 15° were assumed to have low susceptibility to our considered coseismic landslide modes. Low susceptibility terrain was assigned to reflect the relative scarcity of coseismic landslides in modest slopes (below 20°) in datasets with respect to steeper slopes (e.g. Northridge, Harp and Jibson, 1996; Wenchuan, Dai et al., 2011; multiple other events, Meunier et al., 2007) and to eliminate the need to characterize the geotechnical properties of soil and rock for regions unlikely to experience significant coseismic deformation. The upper bound of 15° was selected to be consistent with the observations of Keefer (1984, 2013) that shallow disrupted soil slides, which often dominate coseismic landslide occurrence, may trigger in slopes as shallow as 15°. Low susceptibility terrain was not considered in our later analyses based on the assumption that they would negligibly contribute to the overall coseismic hazard.

2.2. Mode-specific coseismic hazard assessment

2.2.1. Rock-slope failures

We modeled rock-slope failures-including the block slides and falls frequently observed in earthquakes (e.g. Massey et al., 2012)-as Culmann wedge-like masses (Duncan et al., 2014). This methodology captures both the brittle behavior typically associated with rock-slope failures and the planar nature of structural controls (i.e., discontinuities) common in rock masses. To constrain individual block geometries in a geographic information system (GIS) environment, local relief (H) was calculated for each susceptible pixel location based on a moving window analysis. This window size should be selected to best capture the