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Performance-based, seismically-induced landslide hazard mapping of Western Oregon

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ABSTRACT

Seismically-induced landslides can be detrimental to urban communities, often resulting in significant damage and repair costs, blockage of lifeline connection routes and utilities, environmental impacts, and potential for loss of life. Consistent, reliable hazard maps can assist agencies to efficiently allocate limited resources to prepare for these events. This paper presents methodology for evaluating and mapping seismically-induced landslide hazards across a large area utilizing performance-based design strategies. This approach scales site-specific seismic hazard curve analysis techniques to a regional scale evaluation by combining generally available data, including: previous landslide inventories, lidar and photogrammetric topographic data, geologic mapping, NEHRP site classifications based on shear wave velocity (VS30) measurements, and seismic hazard curves for the analysis. These maps can be combined with maps generated for other hazards (e.g., liquefaction) for a fully probabilistic, multi-hazard evaluation and risk assessment. To demonstrate the methodology, a series of landslide hazard maps showing the probabilities of exceeding different thresholds of movement (e.g., 0.1, 0.3, and 1.0 m) were generated for western Oregon. The study area contains weak, wet soils that experience land sliding regularly even without significant seismic activity. The maps show reasonable agreement with landslide inventory and susceptibility maps.

1. Introduction

Natural hazards such as landslides can result in significant material damage, economic loss, and loss of life. Landslides are mainly characterized by the movement of earth materials such as rocks, deposited soils, and manmade fills with downhill and outward failure directions [1,2]. Landslides can be triggered from seismic, climatic or lithospheric stress fields on slopes [3]. Topographic (e.g., slope angle and geometry), hydrologic (e.g., groundwater level, rainfall, water flow), and geologic (e.g., lithology, age, structure, seismicity) conditions are common variables correlated with landslide occurrence [4,5]. However, an improved knowledge in the mechanism of landslide failure and the role of these contributing factors are necessary in order to determine locations likely to fail.

Generally, landslides are widespread in regions with steep slopes where the soil is weak, weathered, and near saturated due to heavy rainfall, and/or the groundwater table is relatively high. Furthermore, landslides can be generated as a result of seismic activities [6,7]. Keefer [8] suggested that many medium to large landslides are the result of either long-term rainfall buildup or seismic impacts. Anthropogenic terrain modifications such as cut slopes, fills, excavations, tree harvesting, and other loading also contribute to landslide triggering. For example, [9] discuss various types of landslides that occurred adjacent to highways after the Sichuan earthquake in 2008. They also note that a substantial portion of damages and injuries from an earthquake are instigated by seismically-induced landslides. Espinosa et al. [10] studied effects of landslides on lifeline routes after earthquakes including property loss, damaged utility services, delayed recovery, and structural failures.

Studying the influence of contributing factors such as slope, geology, source parameters and seismic hazard curve patterns is a first step to prepare for seismically-induced landslide hazards. Because landslides disrupt the earth's surface, detection of prone regions is enhanced through remote sensing, geospatial analysis, and mapping techniques. These data can be utilized to develop landslide inventories and identify vulnerable infrastructure to prepare for future events [11].

Oregon, in particular, is exceedingly prone to landslides due to its wet climate. Landslides in Oregon are estimated to cause $10 million in

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damages annually [12] and they are a challenge for infrastructure such as highways. For example, the coastal mountain range in western Oregon runs near the Pacific Ocean and contains U.S. route 101, which is the only viable road linking seaside communities to each other. During heavy rainfall, various sections of this route are subject to closure when landslides occur, leading to significant traffic delays and safety concerns. Other portions of the highway require frequent maintenance from damages from currently active landslides that are accelerated by wave erosion at the toe of the slopes [13]. In addition, there are only a few routes connecting these coastal communities to more populated regions of the Willamette Valley [14]. All of these traverse through the steep, landslide prone terrain of the coast range. Hence, landslides occurring on these routes are expected to result in significant economic and social impacts to rescue and recovery efforts during other hazards such as strong ground motion and shaking; soil liquefaction, settlement, and lateral spreading; tsunamis; and high intensity coastal storms.

Because of these aforementioned concerns, substantial landslide hazard mapping efforts have been completed in Oregon by the Department Of Geology And Mineral Industry, DOGAMI [12,15,16]. The Statewide Landslide Information Database of Oregon (SLIDO – 3.2) [17] represented in Fig. 1 is an accumulation of reported landslides in Oregon and the result of detailed mapping with lidar technology. This database contains historical precipitation-induced landslide events represented as a point feature class as well as mapped landslide deposits and scarp flanks represented as polygons. DOGAMI frequently updates this database utilizing lidar technology [18], which improves the detection of landslides below the dense forests. Although these efforts have only captured a small portion of the study area; they have shown that significantly many more landslides exist than could be mapped with conventional techniques due to heavy vegetation cover. Hence, despite the fact that Fig. 1 shows the lidar data availability in a large portion of the study area, only a few small sections and quadrangles (see SLIDO 3.2) have been analyzed by DOGAMI to produce more-detailed landslide inventory maps. As a result, it is likely that many landslides have not yet been inventoried than are included in the database.

Lin et al. [19] shows that landslide distribution varies with respect to their triggering mechanism; however, recent studies [13,20] indicate that there is strong likelihood that some of the landslides that have been mapped in Oregon were seismically induced. In many cases, it is unclear whether these landslides have seismic or precipitation origins because of the relative infrequency of significant earthquakes in recent centuries.

1.1. Objectives

To this end, the primary goal of this study is to develop a mapping methodology to quantify the likelihood of seismically-induced landslide occurrence as well as the probability of exceeding certain thresholds of ground displacement considering a wide range of potential earthquake events. While previous work takes significant steps towards the improvement of landslide mapping, the available methods do not achieve all of the objectives desired for this study to produce a methodology, which is:

- **Fully Probabilistic:** The method accounts for major uncertainty sources in the strong ground motion, local topography, and soil strength.
- **Consistent:** The method can be implemented throughout other regions and across a wide range of scales without requiring significant modification. Results from one area should be able to be directly compared with results of a second location.
- **Simplistic:** The method should be based on readily available data while being interactive and user-friendly.
- **Extensive:** The approach can be applied across a large area without problems. Hence, it cannot be reliant on detailed time histories for site response characteristics.
- **Reliable:** The method can be verified by an existing landslide database.
- **Cost-efficient:** It does not rely on limited, expensive data like boreholes and in-situ or laboratory testing of soils, which are not available for an entire region.
- **Compatible:** This method can be integrated with other datasets and analysis (e.g., lateral spreading, flooding and settlement) for a complete hazard analysis.
- **Expandable:** The living maps can easily be updated when new information and data are available.

This methodology was tested for western Oregon (Fig. 1). Mapping landslide hazards for such a large area is challenging because detailed, site-specific data are not available for the entire region.

2. Earthquake induced displacement techniques

Landslide displacements provide a better indicator of failure and damage potential than landslide triggering because the amount of deformation controls the serviceability of a slope and adjacent infrastructure after an earthquake [21]. In 1965, Newmark [22] proposed a simple analysis procedure to model a landslide as a rigid block accelerated from equilibrium by an unbalanced force from the seismic loading. Any earthquake excitation exceeding a critical acceleration will overcome frictional resistance (i.e., shear strength) and initiate sliding of the block. Through two consecutive integrations on the acceleration time-history (using area above the critical values), permanent displacements can be estimated [23].

Additional work has been performed to create new seismic slope displacement models such as the simplified rigid-block, decoupled and coupled methods, and other complicated models. For example, [24–26] empirically assessed the likelihood of a seismically induced landslide based on this method. These relationships are typically multivariate regression equations of parameters calibrated to case history data including:

- Peak Ground Acceleration (PGA), the largest absolute acceleration measured in a strong ground motion,
- Peak Ground Velocity (PGV), the largest velocity measured in an earthquake,
- Spectral Acceleration (S_a), the acceleration measured on an object with given period,
- Equivalent number of cycles (N_{eq}), number of cycles of ground shaking estimated from an earthquake scenario,
- RMS acceleration, defined as the effective acceleration over a given time,
- Yield acceleration (a_y), defined as the minimum acceleration that puts the slope on the verge of failure,
- Earthquake magnitude (M), the maximum trace amplitude, which can be recorded on various seismometers,
- Arias intensity (I_a), a parameter representing all amplitude, frequency content and duration characteristics of a ground motion, and
- Predominant Period of sliding mass (T), the period associated with the highest Fourier amplitude spectrum.

These regression equations all have a probabilistic form to calculate the likelihood of exceeding a threshold displacement. Table 1 summarizes some of the available empirical seismic displacement methods and their necessary input parameters.

Strenk and Wartman [27] evaluated 16 techniques and have shown that these models performed similar to Newmark's method when compared to new case histories. It should be noted that in some cases, Newmark's model would underestimate the actual displacement; as strain increases with the displacement, undrained shear strength will