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The influence of different simplified sliding-block models and input parameters on regional predictions of seismic landslides triggered by the Northridge earthquake

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ABSTRACT

Regional seismic landslide hazard maps are based on predictions of rigid-sliding-block displacement derived from estimates of earthquake ground shaking, topography, geology, and shear strength. The confidence in these predictions requires comparisons with field observations of landslide occurrence during previous well-documented earthquakes. This paper presents a comparison between observed landslides from the 1994 Northridge, California earthquake and predicted landslides based on sliding-block displacement estimates. Seven empirical displacement models, each of which uses a different combination of ground-motion parameters, are investigated to evaluate which models and associated ground-motion parameters best predict seismic landslides. Using best estimates of ground shaking and shear-strength properties from the Northridge earthquake, sliding displacements are calculated and compared with the locations of observed landslides. Only 20–40% of the observed landslides are captured and the total area of predicted landslides is much larger than observed. The ability to predict landslide occurrence accurately depends less on the displacement model and associated ground-motion parameters, and more on the uncertainty in the model parameters, particularly the assigned shear-strengths. Because current approaches do not take into account the spatial variability of shear strength within individual geologic units, the accuracy of the predictive models is controlled predominantly by the distribution of slope angles within a geologic unit. Assigning overly conservative (low) shear-strength values results in a higher percentage of landslides accurately identified but also results in a large over-estimation of the total landslide area. Making more accurate maps of seismic landslide hazards will require methods to define intra-formational variations in shear strength.

1. Introduction

Regional maps that predict the locations of earthquake-triggered landslides commonly are based on estimates of rigid-sliding-block displacements (Newmark, 1965) because these displacements have been correlated with the occurrence of landslides from previous well-documented earthquakes. Wilson and Keefer (1983) showed that the sliding-block model can accurately predict the co-seismic displacement of an individual landslide, and Jibson et al. (2000) demonstrated that regional estimates of sliding-block displacement correlate strongly with mapped locations of seismically triggered landslides. Although the sliding-block model theoretically applies only to block-type landslides that fail primarily by basal shear, Jibson et al. (2000) and McCrink (2001) showed that predicted sliding-block displacements also correlate very well with the occurrence of disrupted falls and slides in rock and debris, which are the most abundant types of earthquake-generated landslides (Keefer, 1984) and which occur through a combination of tensile and shear failure. Since the Jibson et al. (2000) and McCrink (2001) studies, the use of the sliding-block model to evaluate regional seismic landslide hazards has come into general usage (e.g., Carro et al., 2003; Jibson and Michael, 2009; California Geological Survey, 2013), and methods are under development to use these models for rapid prediction of landslide occurrence after earthquakes using ground-motion estimates from products such as ShakeMap (Godt et al., 2009; U.S. Geological Survey, 2012). Given the widespread usage of the sliding-block model, this paper does not address its appropriateness but rather its utility. The landslide distributions predicted by different predictive models for rigid-block displacement are evaluated and the effects of variation of the key input parameters are quantified.

Applying the sliding-block model to predict earthquake-induced landslides at regional scale involves integration of topographic, geologic, geotechnical, and seismological information to develop estimates of sliding displacement. Topographic, geologic, and geotechnical (shear-strength) data are used to generate maps of yield acceleration (i.e., k_y, the acceleration that results in a factor of safety of 1.0 for the slope), and the yield acceleration is combined with the predicted level of ground shaking to estimate displacement. Generally, the topography and geology can be characterized accurately; therefore, the principal sources of uncertainty

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in existing modeling procedures are the characterization of shear strength and seismic ground motion. A further complication is that several different empirical relationships for estimating rigid-sliding displacement have been published (e.g., Jibson, 2007; Saygili and Rathje, 2008), but the differences between results from these models have not been quantified.

This paper addresses two fundamental questions in this maturing field of study: (1) Are there significant differences between the landslide distributions predicted by published models that predict sliding-block displacement, and, if so, which models yield the best results? (2) How sensitive are model results to different shear-strength models? These questions are addressed by comparing the results of the various models and input parameters to the occurrence of landslides triggered by the 1994 $M_w = 6.7$ Northridge, California earthquake (Harp and Jibson, 1995, 1996). The Northridge inventory includes more than 11,000 landslides and is perhaps the best-documented inventory of earthquake-induced landslides yet published. This paper describes the data sets and procedures used in the comparison, presents accuracy assessments for the different empirical models and input parameters considered, interprets the results, and provides recommendations for future research directions that could improve current mapping procedures.

2. Previous seismic landslide comparison studies

The two most important seismic landslide comparison studies analyzed the landslide inventories from the 1994 M_w 6.7 Northridge earthquake (Jibson et al., 2000) and the 1989 M_w 6.9 Loma Prieta, California earthquake (McCrink, 2001). These studies used similar frameworks in which sliding-block displacements were predicted across the study area within a Geographic Information System (GIS) and compared with the mapped locations of landslides triggered by the earthquake. The basic framework is described below, followed by a description of the results from these studies.

A map of yield acceleration (k_y) is generated assuming an infinite-slope condition (Figure 1). If one considers earthquake shaking to occur parallel to the slope, the yield acceleration can be expressed as a simple function of the static factory of safety (FS), the acceleration of gravity (g), and the slope angle (α):

$$k_y = (\mathrm{FS}-1)\cdot g\cdot \sin(\alpha) \quad (1)$$

Based on the slope geometry (the slope-normal thickness of the rigid sliding block, t; the proportion of the block thickness that is saturated, m; and the slope angle, α, Figure 1) and the soil properties (the effective cohesion, c'; effective friction angle, ϕ'; and material unit weight, γ) the static factor of safety for an infinite-slope model is computed as:

$$\mathrm{FS} = c'/(\gamma\cdot t\cdot \sin\alpha) + \tan\phi'/\tan\alpha\cdot(1-m\cdot\gamma_w/\gamma) \quad (2)$$

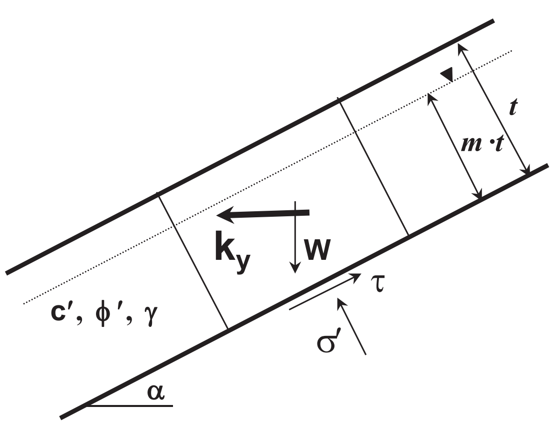

Fig. 1. Infinite slope model for stability calculations.

For regional applications of the infinite-slope model, slope angles are derived from a Digital Elevation Model (DEM), and nominal values for unit weight, block thickness, and saturation thickness are assumed. A 10-m DEM is recommended (Jibson et al., 2000) such that k_y values are developed for a 10-m grid. The main sources of uncertainty in calculating FS and k_y are the assigned material shear strength and thickness of the rigid sliding block. Shear strength is assigned using strength parameters c' and ϕ' obtained from direct shear or triaxial tests. These parameters relate the shear strength to the effective stresses present on the failure plane. Shear-strength data typically are compiled and assigned based on geologic units. Variability within a geologic unit is ignored due to practical constraints. When the shear-strength parameters include non-zero cohesion the sliding-block thickness plays an important role in defining the yield acceleration. k_y increases with decreasing thickness and the effect is significant when the thickness is less than about 2 m. However, the measured shear-strength parameters typically are not representative of the low confining pressures associated with a small sliding-block thickness. Thus, care must be taken to select a sliding-block thickness that is appropriate and consistent with the stress range over which the strength parameters were developed.

The k_y information essentially is a map of seismic landslide susceptibility because it does not predict sliding displacement or landslide occurrence. To develop a map that predicts landslide occurrence, the k_y information is combined with earthquake shaking information to estimate sliding displacement. For regional applications, the ground-shaking level is selected based on a seismic hazard map that defines peak ground accelerations (PGA) or any other ground-motion parameter for a given hazard level, such as 10% probability of exceedance in 50 years (Jibson and Michael, 2009). Having defined the ground shaking and k_y information, displacements are predicted for each 10-m grid cell using an empirical sliding-displacement model or time histories selected to represent the characteristics of shaking. Cells having displacements greater than a specified threshold are predicted to trigger landslides. Commonly used displacement thresholds are 5 and 15 cm (California Geological Survey, 2004; Jibson and Michael, 2009).

2.1. *Jibson et al. (2000) study*

Jibson et al. (2000) considered six 7.5′ quadrangles in the Santa Susana Mountains north of Los Angeles, California that were shaken by the 1994 Northridge earthquake. This was the first earthquake for which a comprehensive data set of slope and soil information, ground shaking, and observed landslides was available to permit a detailed regional analysis. They calculated slope angles from a 10-m DEM and assigned soil shear strengths (c', ϕ') based on results of direct-shear tests from local geotechnical consultants on samples of geologic units in the region. All data used in the study were imported into a GIS platform and converted to layers of gridded raster data at 10-m cell spacing.

Displacements were predicted using an empirical displacement model developed as part of the study (Jibson et al., 2000). This model estimated displacements as a function of k_y and the Arias shaking intensity (I_a, Arias, 1970). To estimate I_a on a regional 10-m grid spacing, they computed the average I_a for the two horizontal components of recorded ground motion from the Northridge earthquake at 189 strong-motion stations and interpolated across the study area using a simple kriging algorithm. The interpolated values of I_a ranged from less than 1 m/s in the northwest corner of the study area to about 5 m/s in the southeast corner, closest to the fault rupture.

Maps of predicted displacement were compared with locations of mapped landslides from Harp and Jibson (1995, 1996). Visual comparisons within a small zone of the larger study area indicated that areas having large predicted displacements generally corresponded to observed landslide locations. Jibson et al. (2000) also quantitatively evaluated a probability of failure (P_f) for different ranges of displacements. Probability of failure was defined as the percentage of cells within a displacement bin that were occupied by landslide source cells, and this probability was