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Empirical predictive relationships for rigid sliding displacement based on directionally-dependent ground motion parameters

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ABSTRACT

The seismic performance of earth slopes is typically quantified by the predicted rigid-sliding-block displacement of a simplified sliding mass. Current empirical predictive relationships for earthquake-induced sliding displacements of slopes are generally developed based on the computed displacement data from a suite of earthquake ground motion time histories. The displacement predicted from these relationships is for the ground motion intensity measures associated with a specific ground motion time history. These intensity measures are different from those for a single definition of bidirectional ground motion that are used in ground motion prediction equations and the distribution of ground shaking following an earthquake (e.g., ShakeMap), which take into consideration ground motion directionality. Therefore, the use of ground motion intensity measures is not consistent throughout the assessment process of seismic sliding displacement of slopes. This paper presents rigid sliding displacements calculated for a set of ground motion records by rotating the horizontal components through all angles. The degree of the azimuthal variation of sliding displacement of slopes with different yield accelerations is examined by analyzing the distribution of sliding displacements in all orientations. Empirical predictive relationships for the orientation-independent earthquake-induced sliding displacement of slopes are developed as a function of directionally-dependent definitions of ground motion parameters. The proposed relationships ensure consistency between the derivation of the ground motion intensity measures and its application in the prediction of sliding displacement of slopes, and consider the potential effects of ground motion directionality on displacement predictions.

1. Introduction

Earthquake-induced landslides have proved to be some of the most damaging seismic hazards in numerous earthquakes. It is hence important to estimate the probability of occurrence of these landslides both in site-specific and regional-scale assessments. Sliding displacement due to earthquake shaking is commonly used to assess the seismic performance of slopes. Newmark (1965) proposed a rigid sliding block model, which assumes that downslope sliding is initialized when the shaking acceleration exceeds the yield acceleration (k_y) of the block, and the block continues to move along a shear surface until the velocities of the block and ground coincide. The sliding displacement (D) is defined as the cumulative relative displacement at the end of ground shaking. Although the rigid sliding block model is a simplified representation of the field conditions, sliding displacements computed in this fashion have been demonstrated to correlate strongly with the occurrence of landslides in previous well documented earthquakes (e.g., Wilson and Keefer, 1983; Jibson et al., 2000).

The yield acceleration of the simplified sliding block and a site-specific ground motion time history are required to compute sliding block displacements. However, it is generally complicated and time consuming to generate an appropriate ground motion time history for calculation of sliding displacements, particularly for regional-scale assessments. Alternatively, empirical predictive relationships for sliding displacement are commonly used. These relationships have been developed as a function of the slope parameter (k_y) and one or more intensity measures (IMs) of earthquake shaking (e.g., Makdisi and Seed, 1978; Ambraseys and Menu, 1988; Jibson, 2007; Bray and Travasarou, 2007; Saygili and Rathje, 2008; Rathje and Saygili, 2009; Rathje and Antonakos, 2011; Hsieh and Lee, 2011; Lee and Green, 2015; Song and Rodriguez-Marek, 2015; Song et al., 2016). While these empirical displacement models cannot replace site-specific seismic response analyses of slopes, they are valuable for the assessment of seismic risk of slopes both at the local and regional levels.

Various deterministic and probabilistic methodologies based on empirical predictive relationships are used to estimate the seismic displacement hazard of slopes (e.g., Rathje and Saygili, 2008, 2009, 2011; Rathje et al., 2014; Du and Wang, 2014; Rodriguez-Marek and Song, 2016). These methodologies involve the prediction of ground motion

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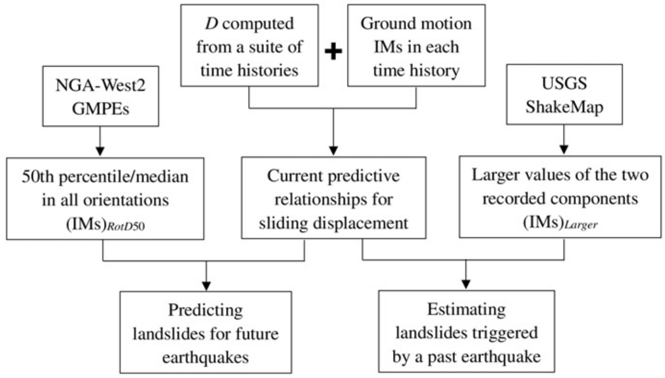

Fig. 1. Flow chart for current methods used for the estimation of seismic slope displacement.

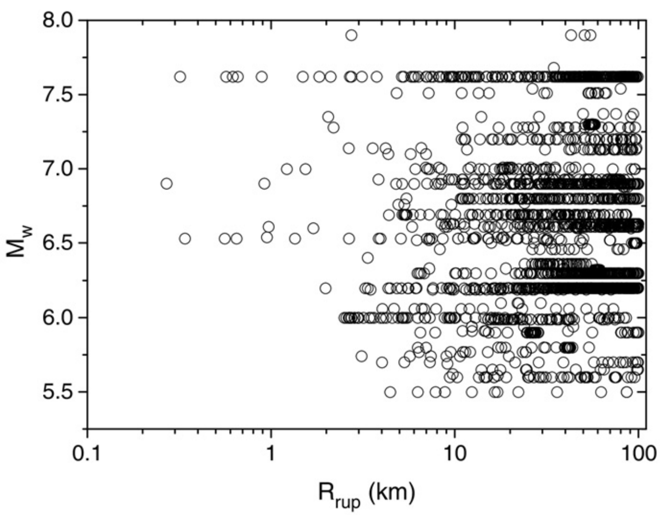

Fig. 2. Distribution of earthquake ground motion records used in this study in terms of earthquake magnitude (M_w) and closest distance to the rupture fault (R_{rup}).

IMs, which is generally accomplished through the use of ground motion prediction equations (GMPEs) or, for the analyses of past earthquakes, using other estimates of ground shaking following an earthquake (e.g., ShakeMap developed by U.S. Geological Survey, USGS, Worden and Wald, 2016). Earthquake ground motions produce translational accelerations in two horizontal components and one vertical component; however, most existing GMPEs, as well as ShakeMap, predict ground motion intensity for a single definition of bidirectional ground motions. For example, the NGA-West2 research program has produced models for predicting the median IMs of a ground motion when rotated over all horizontal orientations (this is referred as the IMs_{RotD50}, Boore, 2010) and the motions shown in maps in ShakeMap are the larger ground motion values, i.e., the larger value observed on the two horizontal components (IMs_{Larger}).

Current empirical predictive relationships for earthquake-induced sliding displacements of slopes were developed by using the calculated displacement data from a suite of ground motion time histories. Hence, the displacements predicted from these relationships are for ground motion IMs associated with a specific ground motion time history. These IMs are different from the predicted ground shaking for future earthquakes from GMPEs, or the best estimates of ground shaking following an earthquake from ShakeMap, and do not take into consideration ground motion directionality. Therefore, the use of ground motion IMs is not consistent throughout the assessment process of seismic performance of earth slopes (Fig. 1). In addition, sliding displacements may be different for ground shaking in different orientations for given predicted or estimated directionally-dependent ground motion parameters (IMs_{RotD50} or IMs_{Larger}). Traditional predictive relationships do not consider the potential effects of ground motion directionality on sliding displacements.

The relationship between ground motion directionality and the dynamic response of potentially unstable slopes has been observed in past earthquakes. For example, Del Gaudio and Wasowski (2011) provide evidence that seismic ground motion on slopes covered by thick colluvia or on deep-seated landslides can have a pronounced directional character, with maxima oriented along the maximum slope direction. Del Gaudio and Wasowski (2011) based these observations on instrumental recordings at Caramanico Terme (Italy), and also point to similar observations in the literature. These observations point to the need to

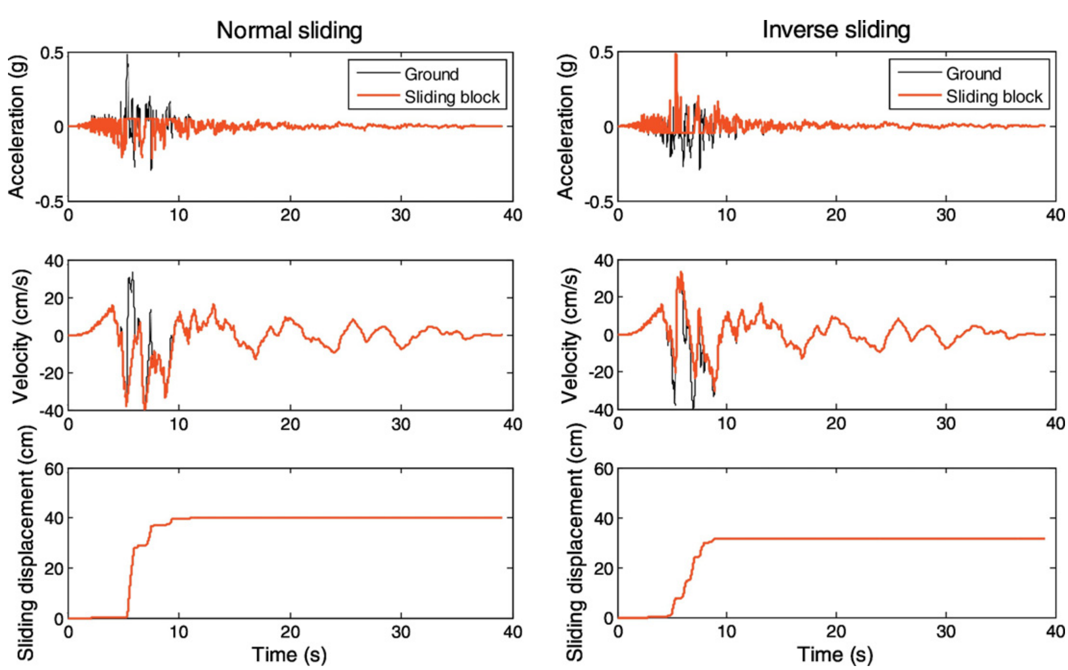

Fig. 3. Time histories of acceleration, velocity and sliding displacement of a rigid sliding block ($k_y = 0.05$ g) for the positive and negative polarities of the El Centro Array #4 ground motion from the 1979 M_w6.5 Imperial Valley-06 earthquake.