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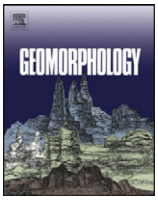

Estimating severity of seismically induced landslides and lateral spreads using threshold water levels

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ABSTRACT

The potential for an earthquake-induced landslide increases when the shear strength of a slope decreases and the hydrostatic pressure increases from the dynamic stresses induced by seismic shaking and/or heavy rainfalls. This paper presents an assessment of seismically induced slope failure in the St. Louis, MO, USA, area; it emphasizes water elevations as the controlling factor, realizing that such levels vary over space and time. We estimated the threshold water table depths to initiate seismically induced landslides in the uplands and liquefaction-induced lateral spreads in the alluvial floodplains under an M7.5 earthquake with a peak ground acceleration of 0.20 to 0.40 g. These threshold water table depths were computed as a function of ground steepness using the Newmark model for rigid block landslides and an empirical regression for lateral spreads. The seismic microzonation was prepared by comparing the map of threshold water table depths and maps of average water levels. The resultant hazard maps suggest that the river bluffs are prone to seismically induced landslides only when the water reaches its highest recorded levels, while much of the floodplains are prone to lateral spreads. Lateral spreads occur more extensively when the water exceeds its normal level.

1. Introduction

Slope failures, which encompass the physical phenomena of lateral and downslope movements of earth material, often are triggered by heavy rainfall and/or moderate to large earthquakes. Rainfall is a major trigger of slope failures in most hilly areas. It raises the water tables below the ground surface, locally elevating pore water pressures and decreasing the shearing resistance of the mass (Chang et al., 2007; Arnone et al., 2011; Santoso et al., 2011). Dynamic stresses induced by seismic shaking reduce the shear strength of the slope and elevate the pore pressure, thereby producing permanent deformations (lurching) and a noticeable downslope movement of earth and rock material (Newmark, 1965; Ambrasey and Srbulov, 1995; Coe et al., 2004). Previous studies have demonstrated that the water table depth is a critical factor in both rainfall-induced and earthquake-induced landslides, and that seismically induced landslides are more easily initiated when the water tables are elevated by rainfall (Johnson and Cotton, 2005; Schulz et al., 2012). For example, soil pore pressures elevated by heavy rainfall prior to the $M_W = 6.6$ Niigata Chuetsu earthquake of 2004 in Japan resulted in widespread slope failures (EERI, 2005; Kieffer et al., 2006).

1.1. Regional seismic landslide maps

Seismic hazards have been mapped to predict and identify failure-prone slopes and thereby to reduce losses from these hazards by establishing mitigation strategies (Fell et al., 2008; EWGCOG, 2009). Regional seismic landslide hazards in hilly terrains have been assessed using the model developed by Jibson et al. (2000). This model is based on Newmark's (1965) rigid block concept that examines the yield acceleration sufficient for displacing blocks along an inclined slope during earthquakes. In low-lying floodplains, lateral spreads can occur in areas with gentle slopes ($<5°$) when underlying sandy soil loses its shear strength through pore pressure increase and becomes liquefied (Wilson and Keefer, 1985; Holzer et al., 2005). This type of slope failure has been estimated using empirical approaches (Bartlett and Youd, 1995; Bardet et al., 2002).

The Newmark model and the empirical approach consider seismologic and geologic factors, including earthquake intensity and duration, physical properties of the materials, water table depths, and slope inclination. Regional hazard mapping is presently being undertaken using geographic information system (GIS) applications, which provide slope inclinations from digital elevation models (DEMs) and enable the spatial analysis of individual grid cells (Carrara et al., 1995; Guzzetti et al., 1999; Wills and McCrink, 2002; Haneberg, 2004a; Kamp et al., 2008; Rapolla et al., 2010).

1.2. Effect of water table depth on seismically induced slope failures

In order to prevent seismically induced slope failures, the ground acceleration and/or the water table depth must remain below their critical

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values to resist the imposed displacements. Seismically induced landslides are usually modeled assuming water table elevations lying below or above the landslide failure surface (Jibson et al., 2000; Miles and Keefer, 2001). The elevation of the groundwater table tends to control the depth of liquefaction as well as the position of the plane of rupture. Slopes underlain by shallow groundwater tables possess the greatest hazard of failure, while those with deeper groundwater tables exhibit the least hazard.

The procedures for creating seismic hazard maps assuming fixed water table depths are limited for detailed microzonation because this approach ignores the normal variations of the water table over considerable areas with the passage of time. Conducting analyses using dry and completely saturated end-member scenarios to represent water table depths may not be appropriate for areas with contrasting geomorphic settings, which exhibit contrasting water table depths over time and space (USGS, 2012; Rogers and Chung, 2013). This implies that the uncertainties associated with water table depths could easily lead to erroneous predictions of seismic hazards.

1.3. Scope of this work

To assess seismic slope hazards, we have developed an alternative approach that varies the depth to the water table and back-calculates the threshold water table depth that would be expected to trigger seismically induced landslides and lateral spreads. Rather than assuming fixed water table depths, this method allows for an assessment of those areas believed most vulnerable to seismically induced movements. The proposed method also helps to promptly predict secondary seismic hazards by producing conditional slope failure maps corresponding to various water table depth scenarios.

This study employed the Newmark method and empirical analysis in the St. Louis metropolitan area, USA, which is exposed to a fairly high risk of earthquakes (Williams et al., 2007; Karadeniz et al., 2009). Few studies of seismically induced slope failures for specific ground motions have been conducted in this area. The resultant map of threshold water table depths was used to assess the incidence of predicted seismic slope failures for both high and normal water table depth scenarios.

2. Regional setting

The study area encompasses a land area of 3320 km^2 in the St. Louis metro area, in the states of Missouri and Illinois, USA (Fig. 1). The area records an annual precipitation between 950 and 1050 mm. The monthly precipitation increases slightly during the spring and summer months, between March and July (NOAA, 1993). The major landforms vary from dissected loess-covered uplands to low-lying floodplains along the Mississippi, Missouri, Illinois, and Meramec Rivers. The floodplains are filled with late Pleistocene terrace deposits and extensive deposits of Holocene alluvium. The dissected uplands are covered by late Pleistocene loess or till deposits (Fig. 2; Goodfield, 1965; Grimley et al., 2001). Slopes steeper than 30° are localized in river bluffs developed in Paleozoic bedrock or its residuum (~3 m thick; Dean, 1977; Grimley and Philips, 2006). The surficial alluvial materials blanketing the bedrock are, on average, 30 to 35 m thick within the major river

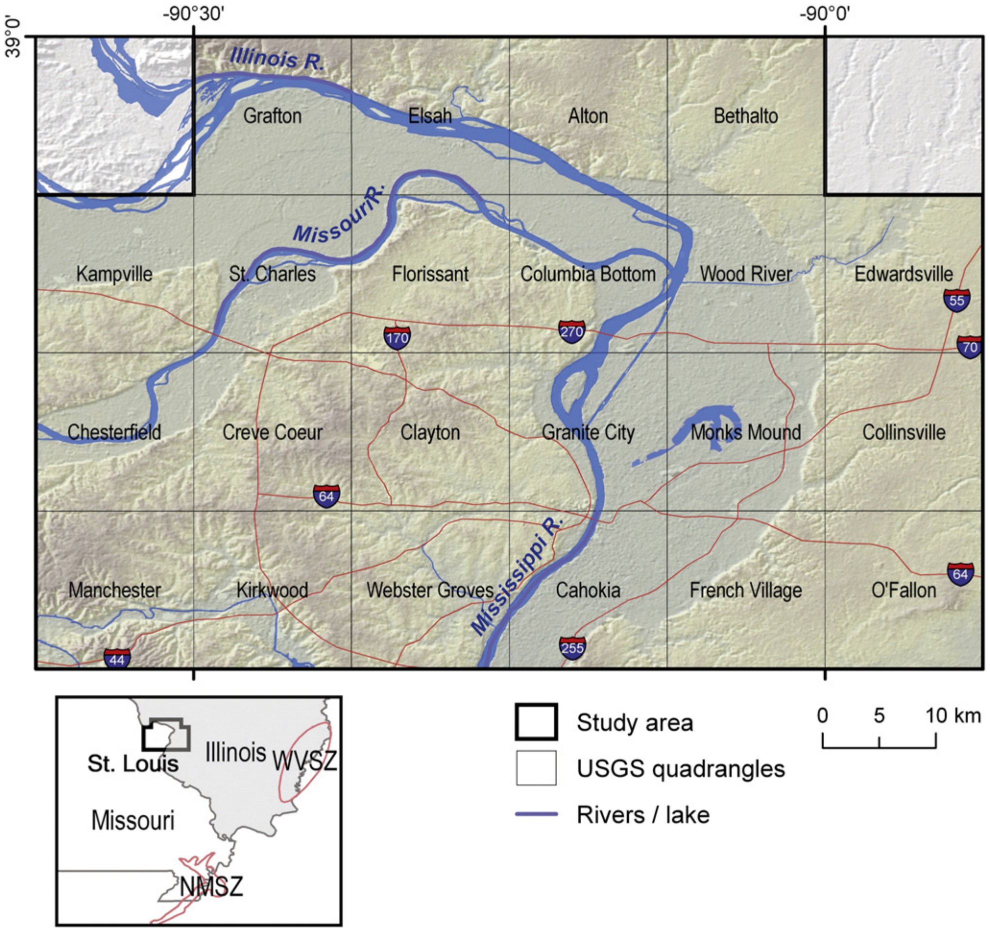

Fig. 1. Location of the study area and adjacent seismic zones (NWSZ = New Madrid Seismic Zone and WVSZ = Wabash Valley Seismic Zone). The study area encompasses 22 quadrangles (1:24,000 scale) in the greater St. Louis area, Missouri and Illinois, USA. The St. Louis area is divided by the state boundary running along the Mississippi River.