Engineering Geology 237 (2018) 76–91

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

# Probabilistic liquefaction-induced lateral spread hazard mapping and its application to Utah County, Utah

Mahyar Sharifi-Mood[a,*], Daniel T. Gillins[b], Kevin W. Franke[c], Jasmyn N. Harper[d], Steven J. Bartlett[e], Michael J. Olsen[f]

[a] Department of Civil, Architectural, and Environmental Engineering, University of Texas, Austin, TX 78712, USA
[b] National Geodetic Survey, National Oceanic and Atmospheric Administration, 1315 East-West Highway, Silver Spring, MD 20910, USA
[c] Department of Civil and Environmental Engineering, Brigham Young Univ., Provo, UT 84602, USA
[d] FM Global, 601 108th Ave NE, Ste 1400, Bellevue, WA 98004, USA
[e] Department of Civil and Environmental Engineering, University of Utah, 122 S. Central Campus Dr., Salt Lake City, UT 84112, USA
[f] School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331 3212, USA

ARTICLE INFO

*Keywords:*
Lateral spread displacement
Probabilistic
Liquefaction
Hazard mapping
Uncertainty modeling
Performance-based

ABSTRACT

Earthquake-induced liquefaction may result in the lateral spread displacement of soil down gently sloping ground or towards a free-face, causing severe and costly damage to various facilities, bridges, buildings and other critical infrastructure. Despite the availability of analytical methods, most engineers currently use empirical or semi-empirical regression models to estimate liquefaction-induced lateral spread displacements at specific sites. However, the application of these regression models for regional mapping over a large geographic areas can be difficult because of challenges associated with the adequate characterization of subsurface soil and groundwater conditions, geotechnical properties, regional topography, and uncertainties associated with the causative seismic loading. To address these challenges, this paper presents a new and fully probabilistic procedure for regional hazard mapping of liquefaction-induced lateral spread displacement. The mapping process is demonstrated through an implementation in Utah County, Utah. To demonstrate the type of lateral spread displacement hazard maps possible, maps corresponding to return periods of 1033 and 2475 years are developed for Utah County, Utah. The proposed procedure incorporates topographical data from airborne lidar surveys and geotechnical and geological data from available maps and subsurface explorations. It accounts for uncertainties in the soil properties, seismic loading, and the empirical models for predicting lateral spread displacement using Monte Carlo simulations.

## 1. Introduction

Seismically-induced soil liquefaction occurs as excess pore water pressure generated by cyclic strains in loose, saturated, and cohesionless soil significantly reduces the shear resistance and stiffness of the soil. A horizontal movement in the soil above a liquefied subsurface layer is called lateral spread (Youd et al., 2001). This type of movement generally develops on gently sloping ground or in the vicinity of a free-face (e.g., river channels, canals or abrupt topographical depression). Lateral spreads have historically resulted in excessive cost and damage to urban communities by rupturing utility lines, destroying foundations, and straining structures. Recent major earthquakes in New Zealand, Japan, Peru, Chile, China, and Haiti have highlighted the need for earthquake engineers to be able to assess, delineate, and quantify the potential for lateral spread hazard when evaluating both new and existing facilities on loose soil sites.

Geotechnical engineers most commonly evaluate liquefaction and lateral spread hazard either analytically or empirically using site-specific techniques. However, some researchers have attempted to quantify and map liquefaction and ground displacement hazard across a larger region (such as a county) in an effort to produce preliminary hazard evaluation for planning, engineering and development purposes. Early liquefaction hazard mapping efforts were generally qualitative and based largely on liquefaction susceptibility correlations with mapped surficial geology. These were implemented out of necessity due to insufficient subsurface soil and groundwater information, or lack of development of predictive models that incorporated important site and soil factors (e.g., Youd and Hoose, 1977; Youd and Perkins, 1978). Later, liquefaction potential mapping efforts (e.g., Anderson et al., 1982; Baise et al., 2006) began considering regional seismic loading in

* Corresponding author at: Advanced Computing Building, 10505 Exploration Way, Austin, TX 78758, USA.
*E-mail address:* mahyar.sh@utexas.edu (M. Sharifi-Mood).

https://doi.org/10.1016/j.enggeo.2018.01.015
Received 18 August 2017; Received in revised form 14 December 2017; Accepted 20 January 2018

addition to liquefaction susceptibility correlations with mapped surface geology to characterize the regional liquefaction triggering hazard. The additional evaluation of the available subsurface geotechnical information across a region in the liquefaction hazard mapping process (e.g., Anderson et al., 1982; Baise et al., 2006; Lenz and Baise, 2007; Olsen et al., 2007; Gillins, 2012) improved the characterization of the liquefaction triggering hazard. These approaches typically used the results for the "critical layer" (i.e., the layer of soil with the smallest factor of safety against liquefaction triggering) in the soil profile to define the liquefaction hazard. However, other researchers have quantified this hazard using a different metric such as liquefaction potential index (LPI) (e.g., Iwasaki et al., 1982; Luna and Frost, 1998; Holzer et al., 2006; Cramer et al., 2008), liquefaction risk index (LRI) (e.g., Lee et al., 2004; Sonmez and Gokceoglu, 2005) or liquefaction severity index (LSI) (e.g., Youd and Perkins, 1987). Each of these indices are calculated by integrating the liquefaction triggering potential across all potentially liquefiable soil layers at a site to a single value.

While integrated liquefaction hazard metrics such as LPI, LSI and LRI have proven useful in mapping the liquefaction triggering hazard across a region, they have been shown to correlate rather poorly with observed lateral spread displacements following major earthquake events because of other relevant factors such as site topography and spatial continuity that are not accounted for in their computation (Maurer et al., 2014; Rashidian and Gillins, 2018). Other investigators have developed lateral spread displacement hazard maps using correlations with mapped surface geology (e.g., Youd and Perkins, 1978) or empirical displacement prediction models in the mapping procedure (e.g., Mabey and Madin, 1993; Olsen et al., 2007; Gillins, 2012; Jaimes et al., 2015; Sharifi-Mood et al., 2017b). These latter displacement hazard maps were developed from a single earthquake scenario developed from either a deterministic seismic hazard analysis or a probabilistic seismic hazard analysis at a single return period. However, these maps do not consider seismic loading from multiple seismic sources and across multiple return periods, nor do they account for variation in ground motion amplification from site response effects (e.g., Bazzurro and Cornell, 2004; Stewart et al., 2014).

This study presents a new and comprehensive procedure to develop fully probabilistic lateral spread hazard prediction maps that account for uncertainties in ground motions, site response, subsurface geotechnical and groundwater information, and lateral spread displacement prediction models. This procedure is based on a performance-based earthquake engineering framework that incorporates probabilistic seismic hazard analysis (PSHA) of the region, site geology base maps, available subsurface geotechnical investigations, available groundwater data, and high-resolution light detection and ranging (lidar) topographic data. The proposed methodology is demonstrated for a study area in Utah County, Utah, resulting in probabilistic lateral spread displacement hazard maps for the area corresponding to the return periods of 1033 and 2475 years.

## 2. Prediction of lateral spread displacements

Currently, lateral spread displacement prediction methods can be divided into three generalized categories (Franke, 2005): (1) empirical prediction models based solely on field data and observation (e.g., Hamada et al., 1986; Bartlett and Youd, 1995; Rauch and Martin, 2000; Bardet et al., 2002; Youd et al., 2002; Gillins and Bartlett, 2013); (2) semi-empirical prediction models based on theoretical derivation that are calibrated against laboratory and/or field data (e.g., Zhang et al., 2004; Faris et al., 2006; Idriss and Boulanger, 2008); and (3) analytical prediction models that numerically compute displacements and that are based on the mechanics of the liquefaction and/or horizontal ground deformation (e.g., Bray and Travasarou, 2007; Seid-Karbasi and Byrne, 2007; Saygili and Rathje, 2008; Lam et al., 2009). Despite the fact that analytical methods continue to make significant progress in their ability to accurately predict lateral spread displacements, empirical and semi-empirical prediction models remain the most popular method for predicting lateral spread displacements among engineering practitioners today because of their simplicity, familiarity, and basis in field performance from case histories of lateral spread (Franke and Kramer, 2014). However, a large amount of aleatory uncertainty is usually associated with these types of predictive models, or in fact with any type predictive model, because of the complexities of the subsurface geology and lateral spread phenomenon and the paucity of well-documented lateral spread case histories for developing robust empirical models.

Bartlett and Youd (1995) originally considered lateral spread events from earthquakes in Japan and the western United States and statistically regressed an empirical prediction model from their resulting case history data that included earthquake moment magnitude, source-to-site distance, several geotechnical soil factors, and slope geometry. Later, Youd et al. (2002) updated their lateral spread case history database and developed a revised multilinear regression prediction model, which remains widely used by engineering practitioners today. Recently, Gillins and Bartlett (2013) simplified the Youd et al. (2002) prediction model by consolidating some of the required geotechnical input factors such as fines content and mean grain size into a single soil classification factor. The Gillins and Bartlett (2013) model was developed specifically for lateral spread hazard mapping applications because it does not require laboratory test results for the soil but instead relies upon visual soil classifications, which are more readily available in most geotechnical field boring logs. The Gillins and Bartlett (2013) multilinear regression empirical model is given as:

$$\log D_H = b_0 + b_1 M_W + b_2 Log\ R^* + b_3 R + b_4 Log\ W + b_5 Log\ S + b_6 Log\ T_{15,cs} + 0.252 + \varepsilon \quad (1)$$

where $D_H$ is the permanent estimated horizontal lateral spread displacement in meters; $M_W$ is the moment magnitude of the earthquake; $R$ is the closest horizontal distance in kilometers from the site to the vertical surface projection of the fault rupture (i.e., the Joyner-Boore distance, $R_{JB}$); $W$ is the free-face ratio (i.e., the ratio of the height to the horizontal distance from the site to the toe of the slope) in percent (%); $S$ is the slope gradient in percent (%); and $R^*$ is a distance parameter used to characterize near-source earthquakes and is computed as:

$$R^* = R + 10^{0.89 M_W - 5.64} \quad (2)$$

$T_{15,\ cs}$, which is the only geotechnical variable in Eq. (1), is the clean-sand equivalent value for $T_{15}$, and is computed as:

$$T_{15,cs} = T_{15}.\ 10^{\left(\frac{-0.683\,x_1 - 0.200\,x_2 + 0.252\,x_3 - 0.040\,x_4 - 0.535\,x_5 - 0.252}{0.592}\right)} \quad (3)$$

where $T_{15}$ is the cumulative thickness (in meters) of saturated, cohesionless, and continuous soil deposits in the upper 15 m of the soil profile with corrected standard penetration test (SPT) $(N_1)_{60} < 15$ hammer blows per 0.3 m, and $x_n$ is the ratio of the cumulative thickness (in meters) of soil with a Soil Index (*SI*) value $n$ with $(N_1)_{60} < 15$ to the total $T_{15}$ for the entire soil column. Thus, $x_n$ will range between 0 and 1, and the sum of $x_1$ through $x_5$ will equal 1. *SI* values and their definitions are provided in Table 1.

Using the Youd et al. (2002) lateral spread case history database, Gillins and Bartlett (2013) solved for the regression coefficients, $b_0$ to $b_6$, for Eq. (3). These coefficients are given in Table 2 according to the

**Table 1**
Soil Index (*SI*) values and their definitions (from Gillins, 2012).

| *SI* | Definition |
|---|---|
| 1 | Silty gravel with sand, silty gravel, fine gravel |
| 2 | Coarse to very coarse sand, sand and gravel, gravelly sand |
| 3 | Sand, medium to fine sand, sand with some silt |
| 4 | Fine to very fine sand, sand with silt, silty sand, dirty sand |
| 5 | Sandy silt, silt with sand |
| 6 | Non-liquefiable, such as cohesive soil or soil with high plasticity |