TESTING NATIONAL AND REGIONAL GEOSPATIAL LIQUEFACTION MODELS IN THE UNITED STATES

J. Zhu, ¹ L.B. Baise, ² E.M. Thompson, ³ and H. Magistrale ⁴

ABSTRACT

Rapid response maps and loss estimates that include the spatial distribution of liquefaction hazard are needed nationally to prepare for and respond to earthquakes. Liquefaction hazard mapping has traditionally relied on detailed geologic mapping and expensive site studies (e.g., standard penetration tests, cone penetration tests). We have developed a logistic regression model to predict the probability of liquefaction occurrence as a function of simple and nationally available geospatial features (e.g., derived from digital elevation models) and standard earthquake-specific intensity data (e.g., peak ground acceleration). As a result of using high resolution, remotely sensed, and spatially continuous data as a proxy for important subsurface parameters and using a probabilistic modeling framework, our geospatial liquefaction model inherently estimates the spatial extent and variability of liquefaction occurrence. In recent work, we developed a geospatial liquefaction model. By using liquefaction occurrence/nonoccurrence data from California earthquakes (1989 Loma Prieta; 1994 Northridge), Seattle earthquakes (1949 and 1965 Puget Sound), the 1964 Prince William Sound Earthquake (Alaska), and limited available data from the 2011 Mineral earthquake, we develop and validate both national and regional geospatial liquefaction models for the United States. By using data from several regions around the country, we evaluate the portability of the geospatial liquefaction model across the United States and conclude the model performs well in natural soils but will require an additional term for artificial fill.

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ABSTRACT

Rapid response maps and loss estimates that include the spatial distribution of liquefaction hazard are needed nationally to prepare for and respond to earthquakes. Liquefaction hazard mapping has traditionally relied on detailed geologic mapping and expensive site studies (e.g., standard penetration tests, cone penetration tests). We have developed a logistic regression model to predict the probability of liquefaction occurrence as a function of simple and nationally available geospatial features (e.g., derived from digital elevation models) and standard earthquake-specific intensity data (e.g., peak ground acceleration). As a result of using high resolution, remotely sensed, and spatially continuous data as a proxy for important subsurface parameters and using a probabilistic modeling framework, our geospatial liquefaction model inherently estimates the spatial extent and variability of liquefaction occurrence. In recent work, we developed a geospatial liquefaction model. By using liquefaction occurrence/nonoccurrence data from California earthquakes (1989 Loma Prieta; 1994 Northridge), Seattle earthquakes (1949 and 1965 Puget Sound), the 1964 Prince William Sound Earthquake (Alaska), and limited available data from the 2011 Mineral earthquake, we evaluate the portability of the geospatial liquefaction model across the United States. By using data from several regions around the country, we evaluate the portability of the geospatial liquefaction model across the United States and conclude the model performs well in natural soils but will require an additional term for artificial fill.

Introduction

Regional liquefaction hazard maps are valuable earthquake hazard products, yet they remain difficult to incorporate into rapid response, loss estimation, and emergency planning efforts. Current regional liquefaction mapping techniques rely heavily on surficial geology maps to identify susceptible units [1, 7, 9, and 18]. Detailed (1:24K) Quaternary geology maps are an effective indicator of liquefaction in seismically active regions [11, 18]. Some regions exposed to high seismic hazards have been able to invest in detailed geology-based liquefaction hazard maps, such as the San Francisco Bay area [7, 9, and 15]. However, there are also many at-risk regions that have not been able to invest the resources necessary to develop these maps. Unfortunately, even where detailed geology-based liquefaction hazard maps exist, they are often not probabilistic and are not easily integrated into rapid response and loss estimation efforts. For

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rapid response and loss estimation, we need broadly available probabilistic liquefaction maps that can be integrated with event-specific shaking intensity maps such as those currently produced by the United States Geologic Survey (USGS) (ShakeMap; [16]) immediately after an event occurs.

In recent work [19], we developed a model that uses simple and nationally available geospatial features (e.g., derived from digital elevation models) and standard earthquake-specific intensity data (e.g., peak ground acceleration) to predict the probability of liquefaction. As a result of using high resolution, remotely sensed, and spatially continuous data as proxies for important subsurface soil properties and using a probabilistic modeling framework, our model inherently estimates the spatial extent and variability of liquefaction occurrence. Compared to the information that is available from a site-specific liquefaction assessment, the explanatory variables that we consider are relatively coarse proxies of the underlying physical parameters controlling liquefaction. Thus, we do not expect to achieve a model that can explain the liquefaction features at a site-by-site scale. Rather, we seek a model that is unbiased with respect to the areal extent of liquefaction, which can therefore identify broad zones of heightened likelihood of liquefaction. This approach to liquefaction modeling is motivated by the need for a globally applicable liquefaction model and implicitly acknowledges that in order to achieve the desired spatial coverage, some precision must be sacrificed relative to a traditional site-specific liquefaction analysis (e.g., [10, 17]) or a detailed geologic analysis (e.g., [7, 9, and 15]).

The Zhu et al. (2013) global geospatial liquefaction (GGL) model was based on mapped liquefaction occurrence/nonoccurrence from the 2010-2011 Christchurch earthquakes [2, 6] and the 1995 Hyogo-ken Nanbu earthquake [8]. The GGL model performed well for two earthquakes in each region. While Kobe, Japan, and Christchurch, New Zealand, are both coastal sedimentary regions, using two separate geologic environments provided a first positive test of model portability. The question still remains: Can the GGL model be used globally to accurately predict liquefaction extent after an earthquake? In this paper, we evaluate the portability of the model using liquefaction occurrence/nonoccurrence data from several earthquakes in the United States (1989 Loma Prieta; 1949 and 1965 Puget Sound; 1964 Prince William Sound). We focus on the San Francisco Bay region, the Seattle region, the Kenai Peninsula in Alaska, and the Virginia region. The San Francisco Bay region experienced extensive liquefaction during both the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake. The greater Seattle region experienced liquefaction during the 1949 and 1965 Puget Sound earthquakes. The Kenai Peninsula experienced extensive liquefaction during the 1964 Prince William Sound earthquake in Alaska. The Virginia region experienced limited liquefaction during the 2011 Mineral Earthquake. Assessing the goodness of fit of the GGL model across these three regions and five earthquakes and determining when the model performs well or not will help inform future generations of the model. For example, we will specifically evaluate whether to incorporate detailed fill or surficial geology when available.

Data

To compare model predictions with observed liquefaction, we review published liquefaction maps for earthquakes in the United States. Table 1 lists the earthquakes used in this study. We focus here on earthquakes where observations of liquefaction were in digital form or could easily
be digitized from maps. Available liquefaction observations for the earthquakes listed in Table 1 are primarily point observations, except for a few polygons in the San Francisco Bay area for the 1989 Loma Prieta earthquake. In all cases, the liquefaction maps focus on observations of liquefaction (rather than non-liquefaction). The quality and completeness of the liquefaction data are highly variable. For point data, we have no information about the spatial extent of liquefaction features, or about the completeness of the mapped liquefaction features.

For the Loma Prieta earthquake, Tinsley et al. (1998) compiled observations at 170 sites that were examined by field personnel after the earthquake for evidence of liquefaction, including sand boils, lateral spreading, settlement, and ground cracking.

For the 1949 and 1965 Puget Sound earthquakes, Chleborad and Schuster (1998) obtained data of ground failures by (1) review of published and unpublished information, (2) interviews with local residents and State and local officials, and (3) field study of selected ground-failure sites. The ground failure types include landslides, ground settlement, ground cracks, sand boils, and miscellaneous effects. A significant number of ground failures occurred in environments thought to be conductive to liquefaction failures [3]. We consider all ground failures in the data as liquefaction related except landslides. Landslide events have a single label but are a combination of failure types, including slumps, rock falls, soil falls, and debris flows. Although slumps often occurred in artificial fill embankments and may be related to liquefaction, slump failures were not included here.

For the 1964 Prince William Sound earthquake, Foster and Karlstrom (1967) documented different types of ground cracks, including ground cracks associated with slumping toward unconfined faces, ground cracks in lowland and valley bottom surfaces, transverse and marginal cracks in modern and elevated tidal flats, and cracks in muskeg areas. The data were based on postearthquake ground observations, supplemented by reconnaissance from fixed-wing planes and by the study of aerial photographs. The ground cracks can be attributed to various processes. For example, the ground cracks in the northeast trending zone in Kenai Lowland may have been due to movement along a fault in the underlying Tertiary rocks [4]. The Foster and Karlstrom (1967) data also included landslides that were excluded from this analysis.

For the 2011 Mineral earthquake, the GEER (Geotechnical Extreme Events Reconnaissance) team members searched for evidence of liquefaction immediately after the earthquake in the epicentral region (i.e., Louisa County, Virginia) and found several small sand boils [5].

Table 1. Summary of the earthquakes in this study.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loma Prieta</td>
<td>1989</td>
<td>6.9</td>
</tr>
<tr>
<td>Puget Sound</td>
<td>1949</td>
<td>6.9</td>
</tr>
<tr>
<td>Puget Sound</td>
<td>1965</td>
<td>6.7</td>
</tr>
<tr>
<td>Alaska</td>
<td>1964</td>
<td>9.2</td>
</tr>
<tr>
<td>Virginia</td>
<td>2011</td>
<td>5.8</td>
</tr>
</tbody>
</table>
The GGL model relies on the following explanatory variables: compound topographic index (CTI), slope-derived shear wave velocity ($V_{S30}$), and magnitude weighted peak ground acceleration ($P GAM$). The CTI is a hydrologic parameter that provides a proxy for soil saturation. $V_{S30}$ is a geotechnical parameter that is commonly used as a proxy for soil density. We use the magnitude scaling factor (MSF; [17]) as a proxy for earthquake duration. The $P GAM$ is PGA divided by MSF. We use PGA from ShakeMaps, which incorporate PGA observations, estimates from ground motion prediction equations, and correlations with macroseismic data. We obtain the explanatory variable layers (PGA, $V_{S30}$, and CTI) for the United States from the USGS websites. We use the $V_{S30}$ values provided by the global $V_{S30}$ server [14]. We use CTI from the Hydro1k database [13]. All of these data are at 30 arc-sec resolution, which is roughly a 900 m x 900 m pixel. Maps of these variables for the San Francisco and Monterey Bay region are shown in Figs. 1a-c.

![Maps of explanatory variables for the San Francisco and Monterey Bay region (a) $V_{S30}$ (b) CTI (c) PGA.](image)

**Methodology**

In Zhu et al. (2013), we developed the GGL model using logistic regression. Logistic regression is a type of generalized linear model that uses logit link function. It is a convenient approach for fitting a model that describes the relationship between a binary outcome and a set of continuous or categorical independent variables. The regression coefficients are estimated with the maximum likelihood method. We tested models with different combinations of candidate variables. We selected the best-performing global model using criteria that combines goodness-of-fit parameters such as Akaike information criterion and p-values, and our knowledge of the physical process that leads to liquefaction. The model outputs the probability of liquefaction (P), which is given by $P = \frac{1}{1 + e^{-X}}$, where

$$X = 24.10 + 2.07\ln(PGA_M) + 0.36CTI - 4.78\ln(V_{S30}). \quad (1)$$

We calculate predicted probabilities of liquefaction for all earthquakes in Table 1 using this model.
Results

The San Francisco Bay area experienced liquefaction during both the 1906 San Francisco and 1989 Loma Prieta earthquakes. Fig. 2 shows the predicted probability of liquefaction and observed liquefaction features for the Loma Prieta earthquake. Liquefaction occurred predominantly in artificial fill near San Francisco and Oakland, and in natural deposits that underlie stream valleys around Monterey Bay. The GGL model performs well in natural soils. The model predicts high probability of liquefaction in the river valleys near the Monterey Bay because these areas are flat with low $V_{S30}$ and high CTI. The geospatial liquefaction model also predicts high probability of liquefaction along the Coyote Creek in northern Santa Clara Valley, in agreement with observations. However, the model performs poorly in the artificial fill regions, such as the Marina District which is a relatively small, flat region on the Northern tip of the San Francisco Peninsula. The predicted probabilities in artificial fill near San Francisco and Oakland are generally very low. The current GGL model does not include a parameter to consider artificial fill or distance to coast (as a proxy for artificial fill). The San Francisco Bay area generally has high $V_{S30}$ values due to the topography, and the CTI is relatively low in the Marina district and other low-lying areas as a result of the low flow accumulation. The GGL model also has poor performance in the southern Santa Clara valley (near the town of Gilroy) where no liquefaction was observed, but the model predicts high probability of liquefaction. The area is covered by fine grained sediment which is not likely to liquefy [9]. The GGL model uses $V_{S30}$ as a proxy for soil density, but does not have a proxy for grain size distribution. Along the western coast of the San Francisco peninsula, there are a few liquefaction features. We think the model is not able to capture those features because the resolution of our explanatory layers is relatively coarse and these coastal flat areas are very narrow.

Liquefaction was observed in the greater Puget Sound region during the 1949 and 1965 earthquakes. (Liquefaction was also observed during the 2001 Nisqually earthquake but we did not acquire the data in time for this paper.) Figs. 3c-d show the predicted probability maps with observed liquefaction features for the 1949 Puget Sound earthquake. Liquefaction related ground failures are distributed over a wide region from the north of Seattle, Washington, to Portland, Oregon. Extensive liquefaction occurred during both events in the central and southern Puget lowland, bordered on the east by the Cascade Range and on the west by the Coast Range. This area is underlain predominantly by Pleistocene glacial sediments. Liquefaction was concentrated in areas near Seattle and Tacoma that are former tidal flats that were extensively filled. The 1949 earthquake also caused failure in the central-southwestern Washington region, mainly in alluvial deposits along river valleys. The GGL model predicts high probability in lowlands in river valleys. The GGL model predicts low probability of liquefaction in the artificial fill near Seattle and Tacoma. The $V_{S30}$ values in Seattle and Tacoma are relatively high as a result of the high slope values in these areas.

Fig. 3b shows the predicted probability map for the 1965 Puget Sound earthquake. This event had a smaller magnitude than the 1949 event and affected a smaller region. Most of liquefaction during this event occurred in artificial fill near Seattle and Tacoma. Again, the GGL model predicts low probabilities in areas with artificial fill.
Figure 2. Maps of the observed liquefaction features and the predicted probability of liquefaction for the 1989 Loma Prieta earthquake

Figure 3. Maps of the observed liquefaction features and the predicted probability of liquefaction for the 1949 and 1965 Puget Sound earthquake
Another important region in the United States where liquefaction has been observed is the Kenai Peninsula and greater Anchorage in Alaska, which experienced extensive liquefaction and ground failures during the 1964 Prince William Sound earthquake. Fig. 4 shows the predicted probability map for Kenai Peninsula for the 1964 earthquake. The map shows the Kenai lowland region where most of the ground failures occurred. This area is covered mostly by thick unconsolidated deposits. Drainage in this area is poor, and numerous lakes, marshes, and muskeg areas make up more than a third of the total surface [4]. Observed ground failures are concentrated in a few regions including a northeast trending zone in the Kenai lowland, around the two largest lakes, Skilak and Tustumena, and in the Kachemak Bay area. All the liquefaction occurrence points lie in areas with high predicted probabilities. Although the model predicts high probability of liquefaction over a wide area, it is difficult to assess if the model over predicts because the liquefaction observations are mapped as points rather than polygons that represent spatial extent.

The 2011 Mineral earthquake is a recent earthquake which experienced limited liquefaction in the eastern United States. Locations of four sand boils observed by the GEER team are shown in Fig. 5 within a few kilometers of the epicenter [5] along with the predicted probability map for the central Virginia region. The model predicts limited areas of high probabilities that contain three of the four sand boils.

Figure 4. Map of the observed liquefaction features and the predicted probability of liquefaction for the 1964 Alaska earthquake
Discussion and Conclusion

The Zhu et al. (2013) GGL model relies on the assumption that loose saturated materials are generally flat with low $V_{S30}$ values. When applying the model, we find out in many areas with artificial fill that either slope-based $V_{S30}$ values are high, or CTI is low, resulting in low predicted probability of liquefaction. Because artificial fill is often unconsolidated and highly susceptible to liquefaction, the GGL model can be improved if we include a parameter to differentiate artificial fill from native soil. In Fig. 6 and Fig. 7, the left panels show the GGL model predictions and observed liquefaction for San Francisco and Seattle. The right panels of the figures show the mapped artificial fill for these regions. The liquefaction features lie predominantly within the fill regions, providing evidence that adding a fill parameter to the model would improve model performance in these regions.

In this paper, we test the Zhu et al. (2013) GGL model on five earthquakes that have resulted in liquefaction in the United States. The results from these earthquakes indicate that the model performance is good in native soils where liquefaction coincides with river channels (for example, the Monterey Bay area and Coyote Creek in the Loma Prieta earthquake) but does not always capture the liquefaction potential of artificial fill (e.g., the Marina district in the Loma Prieta earthquake). Future modifications to the model will include an indicator parameter for native soils versus artificial fill. Unfortunately, artificial fill is not mapped globally and therefore we will have to explore other proxies such as distance to coast or water body to help capture the
common occurrence of artificial fill or otherwise loose, saturated sediments near coasts. For many urban regions in the United States and other countries, artificial fill has been digitally mapped and can be incorporated into the model to further enhance prediction accuracy.

Figure 6. Maps of artificial fill and observed liquefaction features for San Francisco, California

Figure 7. Maps of artificial fill and observed liquefaction features for Seattle, Washington

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References


