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Regional Estimation of Liquefaction-Induced Ground Deformations using a Data-Informed Probabilistic Approach

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ABSTRACT

This paper presents an approach for estimating liquefaction-induced ground deformations on a regional scale in support of risk analyses of spatially distributed infrastructure systems. Logic trees are used to represent uncertainty in subsurface conditions (i.e., results from cone penetration testing and the water table depth) as well as uncertainty between models for liquefaction susceptibility, triggering, and deformations. Finally, a Gaussian process model is used to assign realistic spatial patterns of liquefaction-induced ground failure. The approach described here emphasizes the uncertainty in regional liquefaction risk analysis and takes measures to reduce the potential for overestimation of this risk. The method was developed for application in analyzing the risk faced by spatially-distributed gas infrastructure in California.

Introduction

In this paper, we describe a logic tree-based approach to estimating liquefaction-induced ground deformations. This approach was developed to predict such deformations at any location in the state of California and was undertaken as part of a broader project described in companion papers [1-3]. The first portion of the logic tree focuses on inferring the subsurface conditions based on regionally-available data and accounts for epistemic uncertainty arising from a lack of site-specific information. The second portion of the logic tree uses the inferred subsurface conditions to perform susceptibility, triggering, and deformation analysis using a suite of probabilistic models from the literature. Figure 1 provides a schematic description of the layers in the logic tree.

Inference of Cone Penetration Test Results

The liquefaction susceptibility, triggering, and deformation analysis uses cone penetration test (CPT) results as inputs.

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When such data are not available at all sites of interest, various procedures may be adopted to provide estimates. In this section, we describe an approach for developing a set of typical CPT profiles conditioned upon the site being within a given geologic unit. Each of these CPT profiles is then assigned a weight based on the time-averaged shear wave velocity in the top 30 m (V_{S30}) (measured or calculated using proxy-based procedures) at a given location.

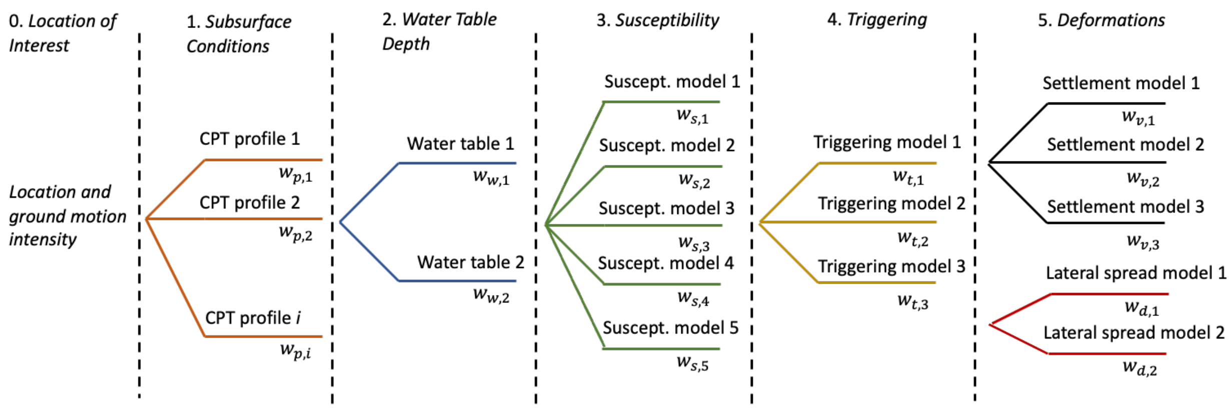

Figure 1. Schematic description of the layers in the logic tree presented in this study. Each branch in each layer is assigned a weight, denoted as w.

We begin with a database of CPT soundings in California that were collected by the USGS [4] and a state geologic map [5]. We consider the following geologic units to be relevant to liquefaction risk analysis: quaternary (Holocene) alluvium for three slope categories (Qal1, Qal2, and Qal3); quaternary (Pleistocene) alluvium (Qoa); and artificial fill over intertidal mud (af/Qi). The CPTs for each relevant geologic unit are grouped using hierarchical clustering. The typical CPT profiles for that geologic unit are the mean q_c and f_s for each of its clusters. Clustering is performed with the definition of the "distance" between CPT i and CPT j being the mean squared error between those CPTs' q_c and f_S profiles added together. Multinomial regression is then performed on the observed CPTs to estimate the probability of being in a given cluster conditioned on $V_{S,30}$. Figure 2 shows the clustering and multinomial model for Qal1.

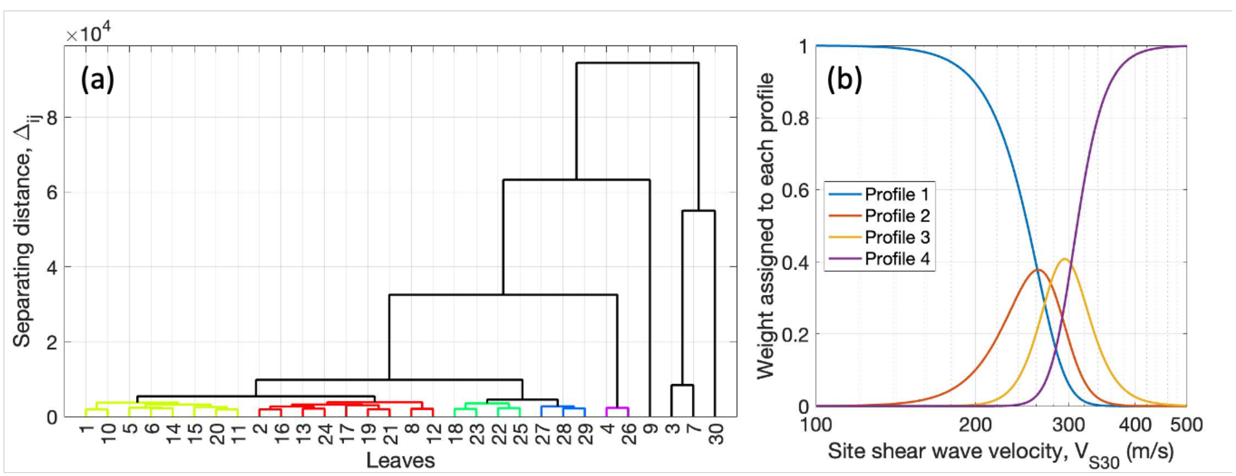

Figure 2. (a) Dendrogram showing the clustering of typical profiles in Qal1 and (b) the multinomial model for assigning weights to those typical profiles as a function of $V_{S,30}$.

Inference of the Water Table Depth

In addition to the CPT profile, liquefaction analyses also require water table depth (wtd) to estimate the total and effective stresses. The second layer of the logic tree combines two estimates of wtd. [6], which can be globally applied, was previously used for regional liquefaction risk analysis by [7]. We also consider well recordings of wtd [8]. We use only recordings made since January 1st, 2000, and give greater weight to more recent recordings. At any arbitrary location, we can obtain two estimates of wtd: one from [6], and one from spatial interpolation of the well data. These estimates are assigned weights depending on the number of wells near a given location.

Susceptibility, Triggering, and Deformation Analysis

For any given CPT profile (i.e., q_c and f_s as functions of depth) and a given wtd, we perform susceptibility, triggering, and deformation analyses, which are reflected in the third, fourth, and fifth layers in the logic tree. We perform susceptibility analysis using CPT-based methods that rely on the soil behavior index (I_c). The susceptibility layer of our logic tree has five branches. On the first branch, the probability that the soil at a given depth is susceptible is 100% if $I_c \leq 2.6$ and 0% otherwise [9]. The probability of susceptibility on the remaining branches is determined using [10]'s logistic models based on I_c. Triggering analysis yields a factor of safety against liquefaction (FS_{liq}) that is used as an input in deformation analysis. We apply three models for FS_{liq} [11-13], three models for settlement-type deformations [14-16], and two models for lateral spread-type deformations [17-18]. Estimates of deformations below a certain threshold (1 cm in this study) are treated as zero.

Feature Creation

The logic tree-based approach described above can yield similar estimates of displacement across large areas of consistent surface geology, water table depth, and ground motion intensity. Applying the logic tree across ground motion scenario maps may therefore overestimate the area that would be affected by liquefaction-induced displacements and provide features of unreasonably large size. The geospatial proxy [6] gives estimates of the portion of the area covered by liquefaction ($\%A_{liq}$) conditioned on the distance to nearby bodies of water, the slope-derived $V_{S,30}$, and ground motion intensity. However, there are no existing methods for assigning liquefaction in space. As part of this project, we developed an empirical spatial correlation model for assigning liquefaction to grid points [19]. The correlation coefficient between two locations separated by a distance of h (in m) is modeled using an exponential function, $\rho(h) = \exp(-3\,h/\ell)$. This function has $\ell = 468$ m for application in California. Liquefaction is assigned to points where the standard normal cumulative distribution function (CDF) of z at site i falls below $\%A_{liq}$ at that site. Figure 3 shows sample maps of the estimated settlement.

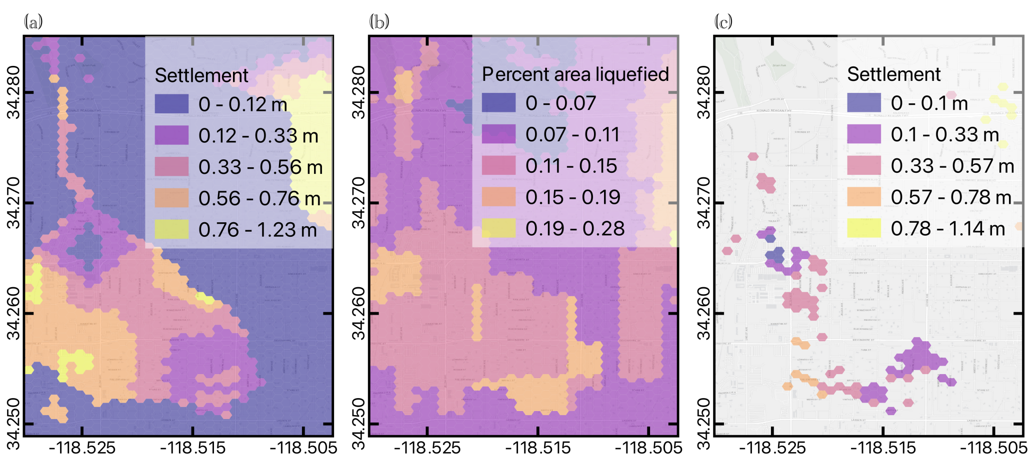

Figure 3. Maps of (a) S obtained from the logic tree, (b) $\%A_{liq}$ [6], and (c) S in liquefaction areas.

Conclusions

In this paper, a regional methodology is presented for estimating liquefaction-induced ground failure deformations and assigning them spatially. The uncertainty around regional estimates of deformations remains high compared to site-specific estimates, but the approach described herein allows rapid application of liquefaction risk analysis procedures without extensive site-specific data. The methodology uses a logic tree to represent uncertainty in subsurface conditions as well as liquefaction susceptibility, triggering, and deformations. Two features of this approach act to reduce overestimation of liquefaction risk. First, the logic tree yields a probability mass at zero displacement, meaning that even areas affected by liquefaction may experience zero deformations. Second, a spatial model for distribution liquefaction was applied, which reduces the total area over which deformations are estimated.

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