LIQUEFACTION POTENTIAL INDEX AND SEISMIC HAZARD MAPPING IN THE SAN FRANCISCO BAY AREA, CALIFORNIA

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ABSTRACT

Liquefaction hazard maps were prepared for Alameda, Oakland, and Piedmont, California, using the liquefaction potential index (LPI) to assess the liquefaction hazard of surficial geologic units. LPI values were computed from 133 cone penetration test soundings conducted in different geologic units in the study region. For an **M**7.08 earthquake on the nearby Hayward fault, the maps predict that 72% of the area underlain by artificial fill and 6% of the area underlain by Holocene alluvial fan will undergo liquefaction. The predictions are consistent with recent experience where similar deposits underwent near-source ground motion.

Introduction

This investigation explores the application of the liquefaction potential index (LPI) to liquefaction hazard mapping in part of the San Francisco Bay area in California. LPI, which predicts the liquefaction performance of the soil profile at a specific site to a depth of 20 m, provides an estimate of the severity of liquefaction at a specific location. Experience with liquefaction in historic earthquakes suggests that surface manifestations of liquefaction such as sand boils, ground cracking, and lateral spreading occur where LPI exceeds some threshold value. Thus, by conducting field surveys that permit computation of LPI for areas underlain by different geologic units, the percent of the area underlain by a geologic unit that will liquefy can be estimated. This enables the quantitative ranking of geologic units with regards to their liquefaction potential.

LPI

LPI was originally developed in Japan to estimate the potential of liquefaction to cause foundation damage at a site (Iwasaki, 1978). The index assumes that the severity of liquefaction is proportional to the:

(1) thickness of the liquefied layer;
(2) proximity of the liquefied layer to the surface; and

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(3) amount by which the factor safety (FS) is less than 1.0, where FS is the ratio of the liquefaction resistance to the load imposed by the earthquake.

It was defined as:

$$LPI = \int_{0}^{20m} F\, w(z)\, dz \tag{1}$$

where

$F = 1 - FS$ for $FS \leq 1$, and
$F = 0$ for $FS > 1$, and
$w(z) = 10 - 0.5\, z$, where z is the depth in meters.

Values of LPI for eq. 1 can range from 0 for a site with no liquefaction potential to a maximum of 100 for a site in which the factor of safety is zero over the entire 20-m-depth range. Whereas LPI relies on the simplified procedure (Seed and Idriss, 1971) to estimate factors of safety, the prediction by LPI is different than that made by the simplified procedure. The simplified procedure predicts the performance of a soil element whereas LPI predicts the performance of the whole soil column to a depth of 20 m.

Iwasaki (1982) and Toprak and Holzer (in press) have compiled case histories that compare LPI with the severity of liquefaction. Iwasaki (1982) concluded that severe liquefaction is likely at sites with LPI greater than 15 and that severe liquefaction is unlikely at sites with LPI less than 5. Toprak and Holzer (in press) correlated surface manifestations of liquefaction with LPI for the 1989 Loma Prieta, California, earthquake and concluded that sand boils and lateral spreading, respectively, occur primarily where LPI ∃ 5 and 12.

Geology

The area that was mapped for liquefaction hazard includes the cities of Alameda, Oakland, and Piedmont, California, which lie on the eastern shore of San Francisco Bay. The surficial geology of the study area was compiled by Graymer (2000) and is shown in Figure 1. The Holocene surficial geology of the region consists of alluvial fan deposits northeast of the original bay shoreline and artificial fill overlying estuarine deposits in most of the area southwest of the original bay shoreline. The alluvial fan deposits consist of multiple units identified primarily on the basis of soil surveys and land-surface morphology. The artificial fills are extensive and consist primarily of sand. Most of the fills were hydraulically emplaced before 1964 without consideration of their vulnerability to liquefaction. The Pleistocene surficial geology consists of Merritt sand, which is primarily an aeolian deposit, and older inactive alluvial fan deposits. The area is intersected by the active Hayward fault (Lienkaemper, 1992).

Liquefaction Hazard Maps

The USGS conducted 133 CPT soundings in both Holocene and Pleistocene surficial units. LPI's were computed for each CPT sounding using a scenario earthquake on the Hayward fault; an **M**7.08 earthquake with a peak horizontal acceleration of 0.5 g. This scenario assumes rupture of both the north and south segments of the Hayward fault and is a worse case situation

(Working Group on California Earthquake Probabilities, 1999). The estimated recurrence time of the scenario earthquake is 523 yr. Soil sampling adjacent to selected CPT soundings was conducted to ensure soils were classified properly from the CPT measurements.

To identify the hazard level of each geologic unit, LPI values were grouped by surficial geologic units and cumulative distributions were prepared (Figure 2). Although the geologic mapping identified subunits within the Holocene alluvial fan complex, these subunits were not geotechnically distinguishable. Accordingly, LPI's for these subunits are lumped together in Figure 2. Based on an LPI∃5 as the value at which surface manifestations of liquefaction occur, Figure 3 indicates that 72, 25, and 6%, respectively, of the areas underlain by artificial fill, Merritt sand, Holocene alluvial fan will liquefy. The Pleistocene alluvial fan has LPI#3 and is not anticipated to contribute significantly to liquefaction for the scenario earthquake. Note that the grouping of LPI by surficial geologic units ignores the contribution to LPI of underlying older geologic units when the surficial unit is less than 20 m thick. Fortunately, within the present study area, liquefaction potential tends to be dominated by the unit exposed at the land surface, at least where the surface unit is saturated.

The preliminary liquefaction hazard map is shown in Figure 3. In addition to using mapped boundaries of geologic units to outline areas with different degrees of hazard, the landward extent of saturated Holocene alluvial fan material was determined and used as a boundary. To produce this hydrogeologic boundary, a thickness or isopach map of the Holocene alluvial fan material was created. Thickness was measured from the CPT soundings and inferred from commercial borings. A map of depth to ground water was also created and the intersection of these surfaces was determined with a geographic information system to establish where Holocene alluvial fan material was unsaturated and not susceptible to liquefaction. The liquefaction hazard in the area directly underlain by unsaturated Holocene alluvial fan material derives from the deeper underlying saturated Pleistocene material. Because liquefaction in small parts of the Pleistocene alluvial fan cannot be completely precluded, its hazard level is shown as <1% on the hazard map.

Conclusions

The combination of LPI computed from CPT soundings with surficial geologic mapping provides a quantitative approach for regionally mapping liquefaction hazard by specifically predicting how much of the area underlain by a geologic unit will liquefy. In the present investigation, the percentages of areas that are predicted to liquefy are consistent with experience in recent earthquakes where deposits have experienced near-source ground motion. For example, the large percentage of the artificial fill that is predicted by this investigation to liquefy is consistent with the extensive liquefaction of loose fills during the 1995 earthquake in Kobe, Japan (Hamada, 1995). Similarly, the small, but nevertheless significant, area predicted to liquefy in areas underlain by Holocene alluvial fan deposits is consistent with U.S. experience in the 1994 Northridge, California, earthquake, where a small percent of the alluvial fan liquefied (Holzer, 1999). The minor contribution of Pleistocene alluvial fan units is also consistent with historical experience. The prediction that 25% of the area underlain by Pleistocene(?) Merritt sand will liquefy is high for Pleistocene materials. Most of the liquefaction is predicted to occur in a small portion of the Merritt sand that crops out in Oakland. The susceptible material appears to be associated with a loose-sand facies that may be of limited extent. Drilling and sampling is planned in Fall 2001 to improve understanding of this part of the Merritt sand.

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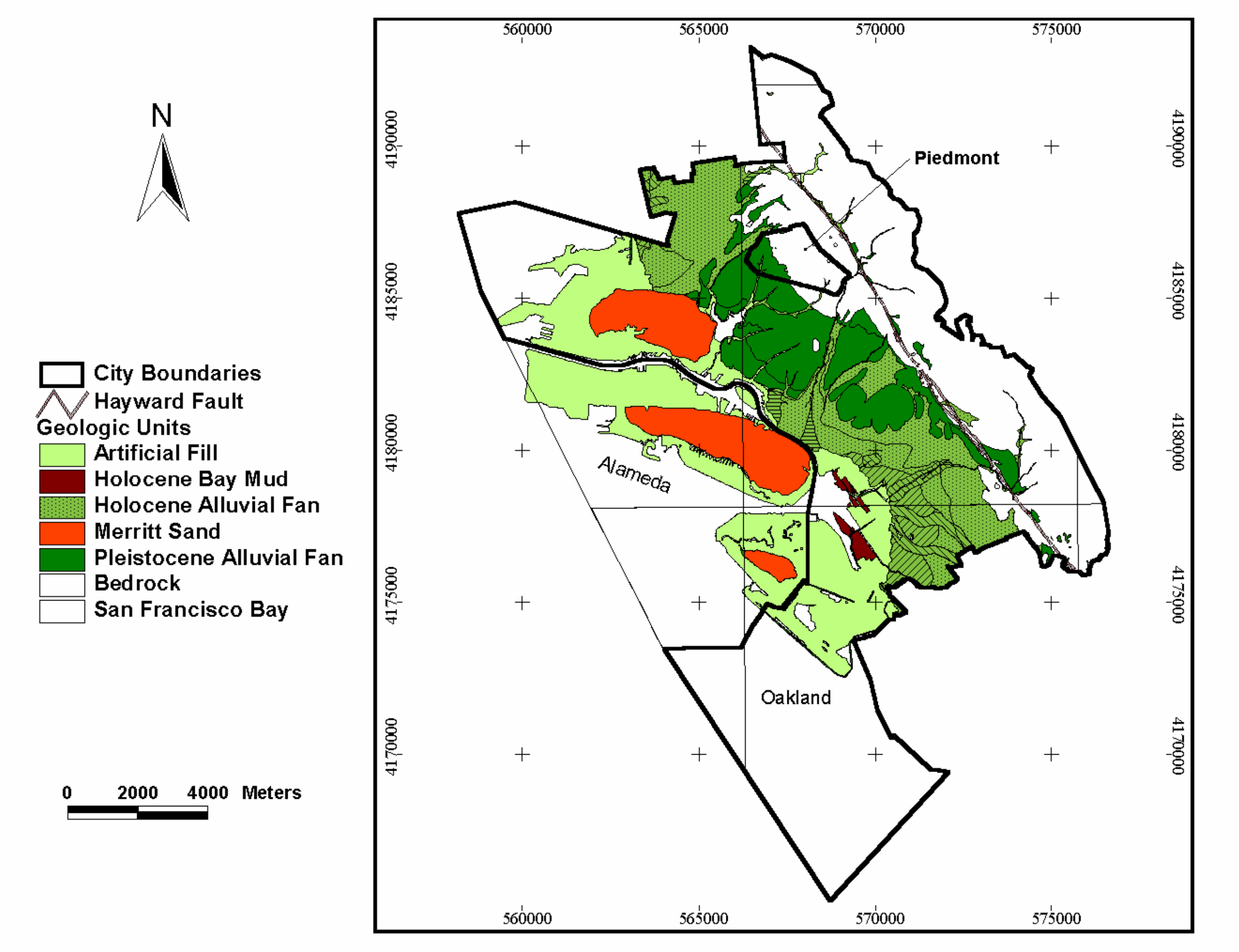

Figure 1. Surficial geologic map cities of Alameda, Oakland, and Piedmont, California (modified from Graymer, 2000). Original shoreline is the eastern boundary of the artificial fill. Units are colored by geologic age or epoch. Separate units of same geologic age are shown by different patterns. UTM grid is in meters and is for zone 10S.

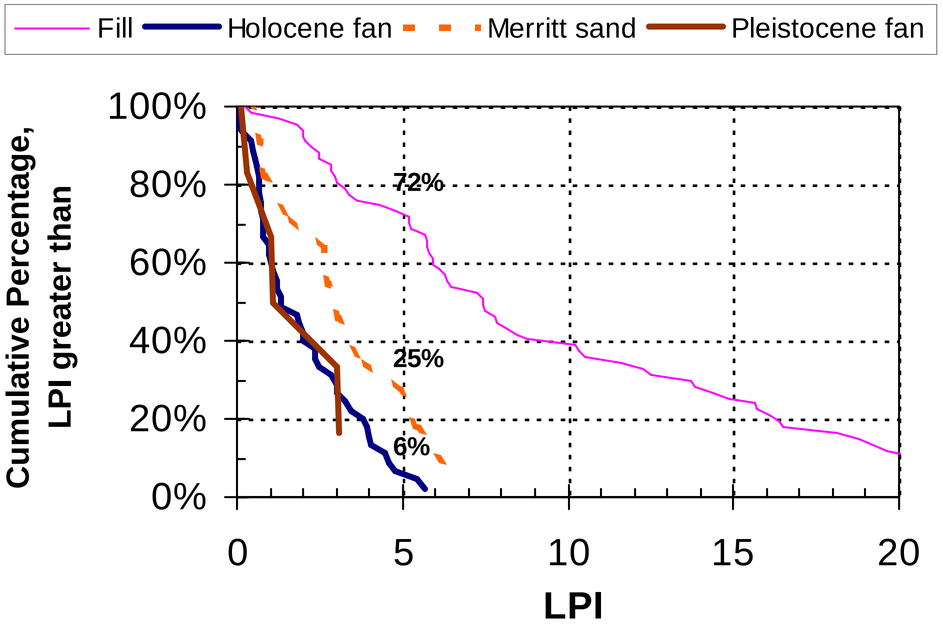

Figure 2. Cumulative percentages of LPI for surficial geologic units in Alameda, Oakland, and Piedmont, California, for an **M**7.08 earthquake on the Hayward fault.

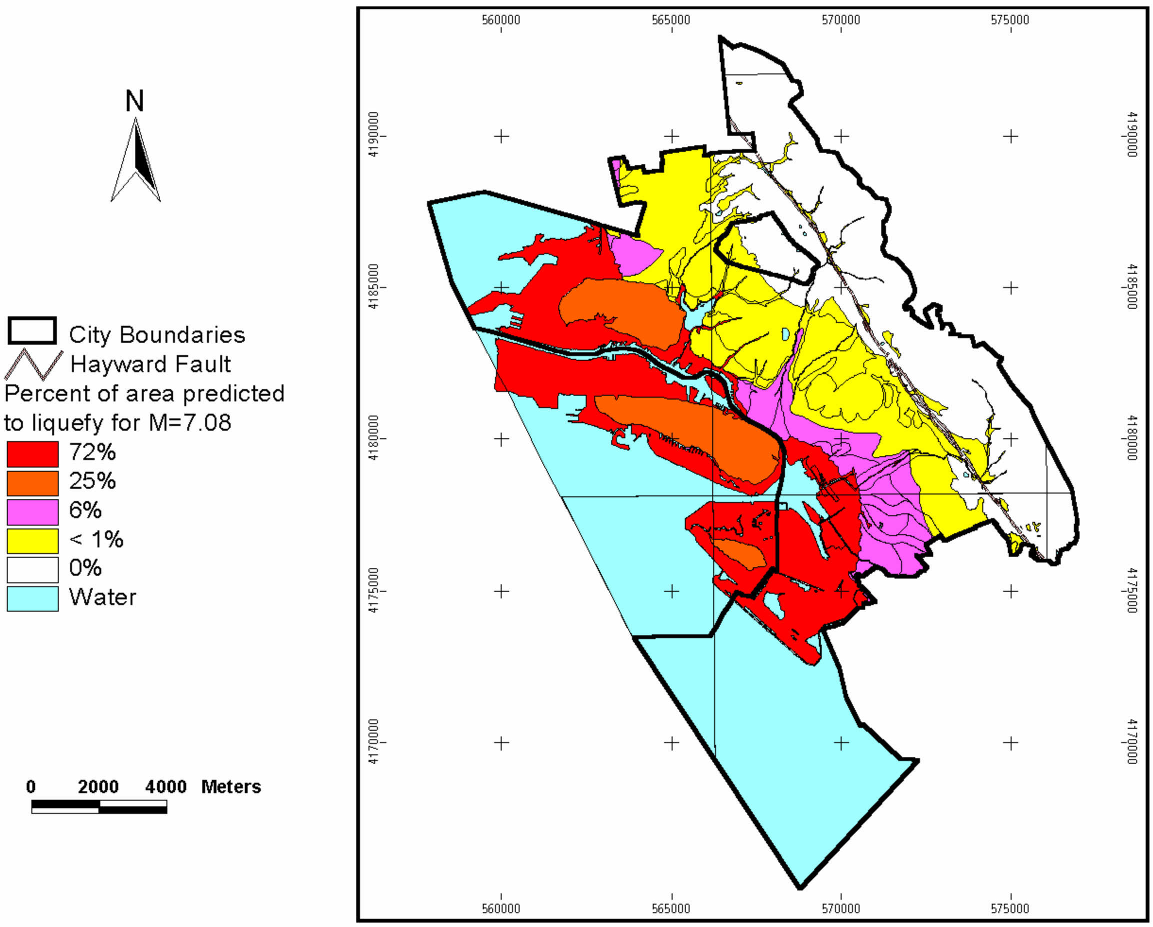

Figure 3. Preliminary liquefaction hazard map of Alameda, Oakland, and Piedmont, California, for an **M**7.08 on the Hayward fault. Colors show areas where different percentages of the land area will experience liquefaction. Boundaries of geologic units from Figure 1 are also shown.