

Liquefaction Susceptibility Mapping in Memphis/Shelby County, TN

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Introduction

Urban seismic hazard maps are being developed for the Memphis, Shelby County, TN region by the U.S. Geological Survey (USGS). These maps include liquefaction potential maps at a scale of 1:24,000. Based on the geologic and subsurface information compiled by the USGS and SPT and CPT data compiled from other researchers, a methodology for producing liquefaction potential maps is developed.

Liquefaction potential has been defined in terms of the liquefaction potential index (*LPI*). The LPI considers the factor of safety (*FS*) against liquefaction for soil deposits in the upper 20 meters. The factor of safety is weighted as a function of depth to obtain an overall estimate of the liquefaction on the entire soil deposit. Liquefaction maps are based on the probability of exceeding a particular LPI value that has been correlated to minor and major damage.

This study utilizes cone penetration test (CPT) data and standard penetration test (SPT) data compiled for the Memphis area to determine the liquefaction potential index of each geologic region. Surficial geologic maps were obtained from the Center for Earthquake Research and Information (CERI) and the USGS at the University of Memphis (Tucker, 2003). Figure 1 shows the geologic map of the seven quadrangles in the Memphis area.

Previous Studies

An initial analysis of the CPT data is discussed in Rix (2002). A limited number of CPT profiles were compiled in the Memphis area (McGillivray, 2001; Liao et al., 2002). A stochastic approach is used to simulate CPT profiles that incorporate the statistics of the measured profiles. The mean, standard deviation, and autocorrelation function are used to produce simulated profiles. The autocorrelation function is calculated to determine the spatial correlation of CPT data in the vertical direction. The LU decomposition algorithm contained in GSLIB is used to generate CPT profiles (Deutsch and Journel, 1998). The LPI for each stochastically simulated profile is calculated. A subsequent analysis is performed to validate the stochastic simulation procedure using CPT data from the East San Francisco Bay area in California. The results from the stochastically simulated CPT profiles in Memphis are compared with the results from CPT profiles in California to determine if the simulation accurately models the heterogeneity and variability of measuring geologic deposits in situ.

SPT data compiled by Ng et al. (1989) and Hwang et al. (1999) is used to determine the liquefaction susceptibility of the Memphis area. The SPT data set is larger than the CPT data set. However, information regarding SPT testing procedures and soil type is often incomplete. Assumptions and analysis of the SPT data is discussed below.

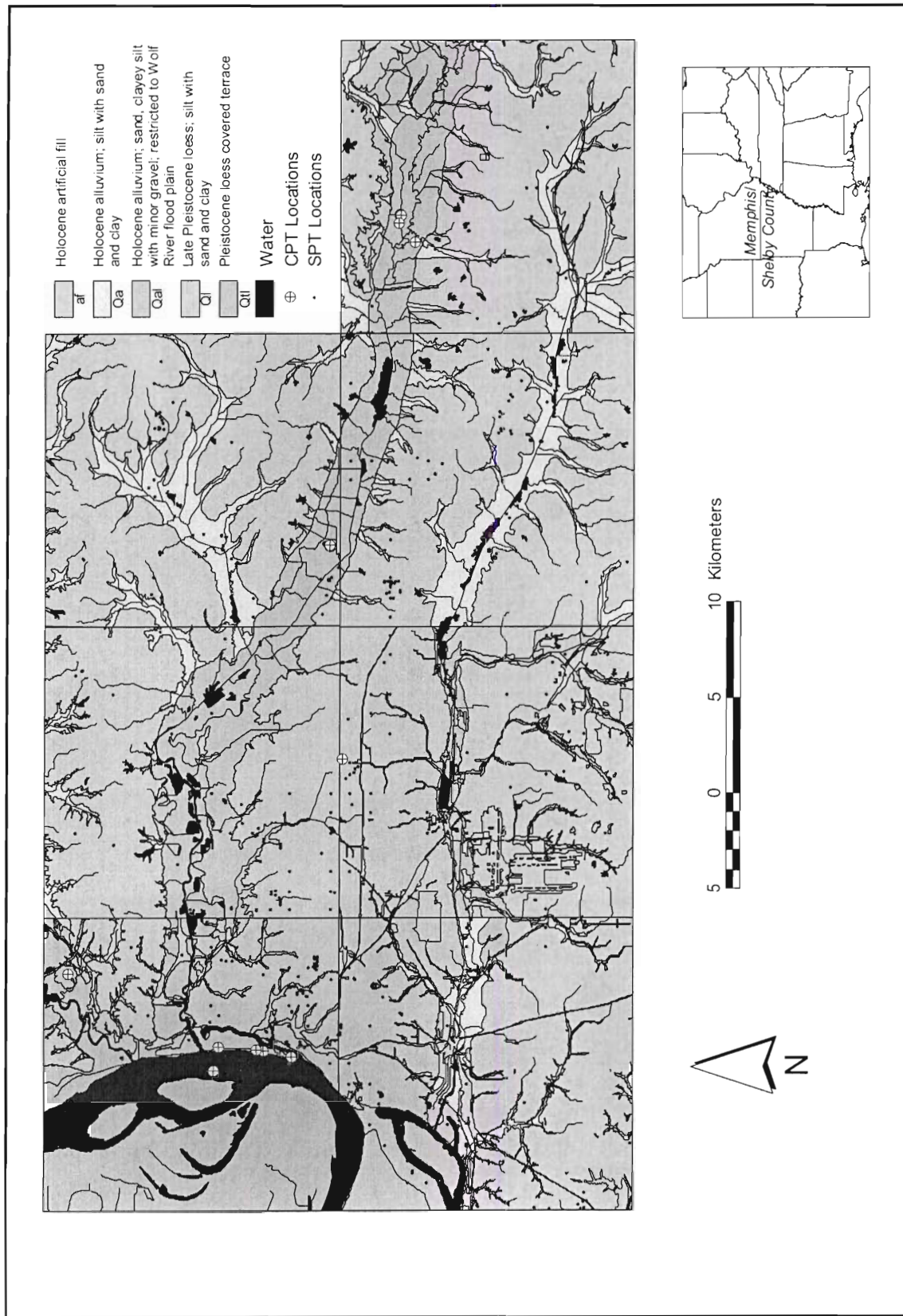


Figure 1 Near-surface geology of Memphis and location of SPT and CPT sites.

Investigations

SPT Data

Ng et al. (1989) and Hwang et al. (1999) compiled standard penetration test (SPT) data for the Memphis Metropolitan area. This data set was analyzed to determine the factor of safety against liquefaction for each site using the simplified procedure developed by Seed and Idriss (1971) and Youd et al. (2001). The factor of safety is subsequently used to calculate the liquefaction potential index defined by Iwasaki et al. (1978) and Iwasaki et al. (1982). Based on the liquefaction potential index calculated for sites within a particular geologic region, the probability of exceeding a particular *LPI* was determined. The results were compared with the results previously obtained from the CPT data. Both sets of results will be incorporated into final liquefaction potential maps.

Simplified Procedure

The 1997 National Center for Earthquake Engineering Research (NCEER) workshop outlined a method of evaluating liquefaction resistance based on the simplified procedure. The seismic demand is given by the cyclic stress ratio (CSR)

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{vo}} \right) = 0.65 \left(\frac{a_{max}}{g} \right) \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) r_d$$

(Youd et al. 2001) where a_{max} is the peak ground acceleration, g is the acceleration due to gravity, σ_{vo} and σ'_{vo} are the total and effective vertical overburden stresses, and r_d is the stress reduction coefficient given by

$$r_d = 1.0 - 0.00765z \quad \text{for } z \leq 9.15m$$
$$r_d = 1.174 - 0.0267z \quad \text{for } 9.15m < z \leq 23m$$

(Youd et al., 2001) where z is the depth.

The depth to the groundwater table was determined from the data compiled by Hwang et al. (1999). Based on this subsurface data, 464 groundwater wells were used to produce a contour map of the depth to the groundwater table. An average depth of 6 meters was used for analyses. Analyses were performed for a_{max} values of 0.1 g , 0.2 g , 0.3 g , 0.4 g , and 0.5 g .

The cyclic resistance ratio (*CRR*) defines the shear resistance of the soil and is based on the results of SPT, CPT, or shear wave velocity measurements. The *CRR* delineates which sites will liquefy and which will not. For SPT data, the *CRR* for a moment magnitude of 7.5 is given as

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{(10(N_1)_{60cs} + 45)^2} - \frac{1}{200}$$

where $(N_1)_{60cs}$ is the equivalent clean sand standard penetration resistance (Youd et al., 2001). The equivalent clean sand standard penetration resistance is obtained by correcting the measured standard penetration resistance (N_m) for effective overburden stress, hammer energy ratio, borehole diameter, rod length, samplers with or without liners, and fines content. Due to the limited information available from

the SPT data, corrections were only performed for effective overburden stress. The corrected standard penetration resistance $((N_1)_{60})$ was calculated by

$$(N_1)_{60} = N_m C_N$$

where the correction for effective overburden stress, C_N , is defined as

$$C_N = (P_a / \sigma'_{vo})^{0.5}$$

and P_a is 100 kPa.

A fines content correction was applied to the calculated $(N_1)_{60}$ value to obtain an equivalent clean sand standard penetration resistance $((N_1)_{60cs})$ given by

$$(N_1)_{60cs} = \alpha + \beta(N_1)_{60}$$

where the coefficients α and β are defined below

$$\alpha = 0 \quad \text{for } FC \leq 5\%$$

$$\alpha = \exp\left(1.76 - \left(\frac{190}{FC^2}\right)\right) \quad \text{for } 5\% < FC < 35\%$$

$$\alpha = 5.0 \quad \text{for } FC \geq 35\%$$

$$\beta = 1.0 \quad \text{for } FC \leq 5\%$$

$$\beta = \left(0.99 + \left(\frac{FC^{1.5}}{1000}\right)\right) \quad \text{for } 5\% < FC < 35\%$$

$$\beta = 1.2 \quad \text{for } FC \geq 35\%$$

where FC is the fines content. The fines content was approximated from the Unified Soil Classification System (USCS).

Liquefaction Potential Index

The liquefaction potential index (LPI) is defined as (Iwasaki, 1982)

$$LPI = \sum_{i=1}^n w_i S_i H_i$$

where w is the depth dependent weighting function given as

$$w_i(z) = 10 - 0.5z$$

S is the degree of severity calculated as

$$S = 1 - FS \quad 0 \leq FS \leq 1$$

$$S = 0 \quad FS > 1$$

where FS is the factor of safety defined as the ratio of the cyclic resistance ratio to the cyclic stress ratio, and H is the depth of the layer of interest.

Initial SPT Analysis

SPT profiles from the Ng et al. (1989) and Hwang et al. (1999) databases were selected based on the completeness of the profiles. Since deposits in the upper 20 meters are used for liquefaction potential analyses, SPT profiles extending to a minimum depth of 15 meters were selected for analysis. A total of 725 profiles were identified and shown in Figure 1. The soil type is also needed for liquefaction analysis for SPT profiles. The databases contain the Unified Soil Classification System (USCS) soil type at each depth. However, this information is not complete for all profiles. Therefore, profiles were grouped into six categories based on the level of information available:

- (1) Complete SPT profile to a depth of 20 meters and complete USCS information.
- (2) Complete SPT profile to a depth of 20 meters but incomplete USCS information.
- (3) No SPT data below 18 meters and complete USCS information to 18 meters.
- (4) No SPT data below 15 meters and complete USCS information to 15 meters.
- (5) No SPT data below 18 meters and incomplete USCS information throughout profile.
- (6) No SPT data below 15 meters and incomplete USCS information throughout profile.

Several assumptions were used in the initial liquefaction analysis. For SPT profiles not extending to 20 meters, the last N_m measured was assumed for depths up to 20 meters. For profiles with incomplete USCS information, the soil type was assumed to be sand since this is the most conservative estimate. Table 1 lists the USCS soil types and assumed fines content for liquefaction analysis. The soil type for a few profiles was defined by the AASHTO classification system. Table 2 lists the assumed USCS soil type for the AASHTO classification based on the most probable soil type given by Das (1993).

Table 1 Assumed fines content for USCS soil type

<i>USCS</i>	<i>Assumed Fines Content (%)</i>
No classification (SW assumed)	0
GW, GP, SW, SP	0
GC, GM, GC-GM, SC, SM, SC-SM	12
CH, CL, MH, ML, OL, OH, CL-ML	50
GW-GM, GW-GC, GP-GM, GP-GC, SW-SM, SW-SC, SP-SM, SP-SC	5

Evaluation of SPT Assumptions

The soil type assumption of sand with no fines is a conservative estimate that may produce higher LPI values than may actually exist. Similarly, the assumption that N_m measured that the greatest depth was valid for depths to 20 meters may also be too conservative and produce high LPI values that are not realistic. These assumptions were evaluated by using a sample of the complete SPT profiles (category 1 above) and creating "incomplete" profiles by eliminating data and using the assumptions discussed above. By using this approach, categories 2 through 6 discussed previously were simulated and compared with the complete profiles. For each case, the LPI was calculated. The ratio of the LPI for the complete profiles to the LPI for the incomplete profiles was calculated. Figure 2 shows the median of the ratios calculated for each case. The median was selected for comparison rather than the mean since the median

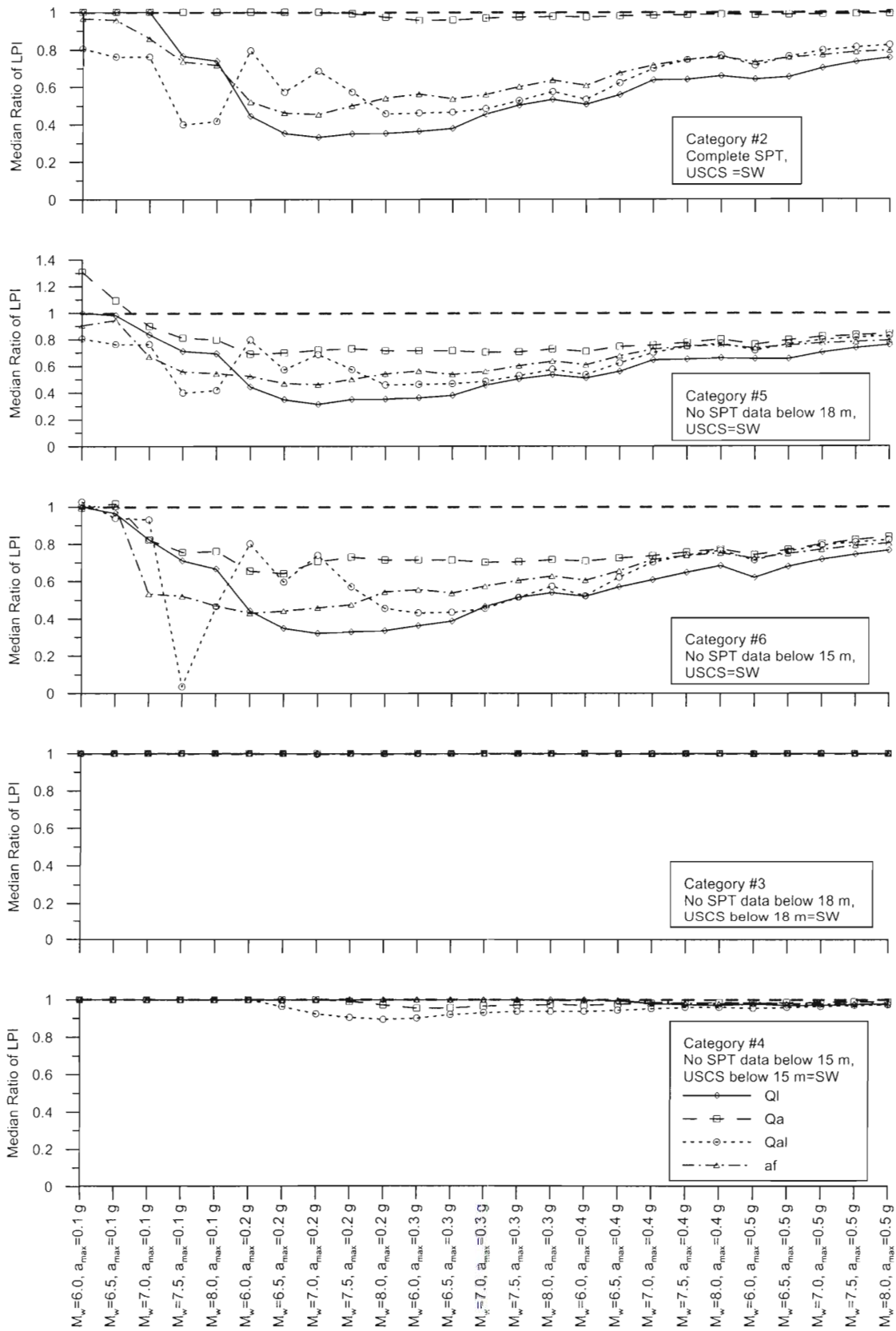


Figure 2 Comparison of ratio of LPI values.

is not affected by outliers in the data. A median ratio of 1 represents no difference between the *LPI* of the complete data and incomplete data whereas a median ratio below 1 shows a larger *LPI* for the incomplete data than the complete data. Therefore, median ratios below 1 represent a conservative estimate.

Table 2 Assumed USCS soil type for AASHTO classification

<i>AASHTO Classification</i>	<i>USCS Soil Type</i>
A-1-a	GW
A-1-b	SW
A-2-4, A-2-5	SM
A-2-6, A-2-7	SC
A-3	SP
A-4	ML
A-5	MH
A-6	CL
A-7-5	MH
A-7-6	CH

The assumption of N-value below 15 meters or 18 meters does not produce significantly conservative *LPI* values. For the case of profiles not extending below 18 meters, the assumption produces no measurable difference. For the case of profiles extending below 15 meters, the assumption may be up to 10% conservative. However, the soil type assumption significantly influences the *LPI*. If limited information concerning soil type is available, an assumption of clean sand may produce *LPI* values that are 60% conservative. Therefore, based on this analysis, an assumption of the soil type should be based on the known geology. For each geologic region, a typical soil type profile was developed from complete soil type profiles available within that region. The typical soil profile is based on the most commonly identified soil type at each depth. Table 3 lists the typical soil type profiles for each geologic region. These soil type profiles were used to produce more realistic soil type profiles and improve the estimate of *LPI*.

The SPT data was analyzed using the new soil type profiles and the *LPI* was recalculated. Figure 3 compares the *LPI* values calculated using the original assumption of soil type (sand) to the *LPI* values calculated using the adjusted soil type profile. The adjusted values include all profiles including those not affected by the soil type assumption observed in Figure 2.

Evaluation of GWT depth assumption

The depth to the groundwater table was based on data from 464 groundwater wells (Hwang et al., 1999). Contour maps of the depth to the groundwater table were produced from the available. In general, the groundwater table ranged in depth from 2 meters to 12 meters. For the liquefaction analysis, a constant depth of 6 meters was assumed. This assumption was evaluated by comparing with groundwater table depths of 2 meters, 4 meters, 8 meters, 10 meters, and 12 meters.

Figure 4 compares the effect of the depth to the ground water table. At low magnitudes and low peak ground accelerations, the effect of the ground water table is greater and decreases with both magnitude and peak ground acceleration. A greater depth to the ground water table produces lower values of *LPI* whereas a lower depth to the ground water table produces larger values of *LPI*. However, the constant value of 6 meters was used for all analyses.

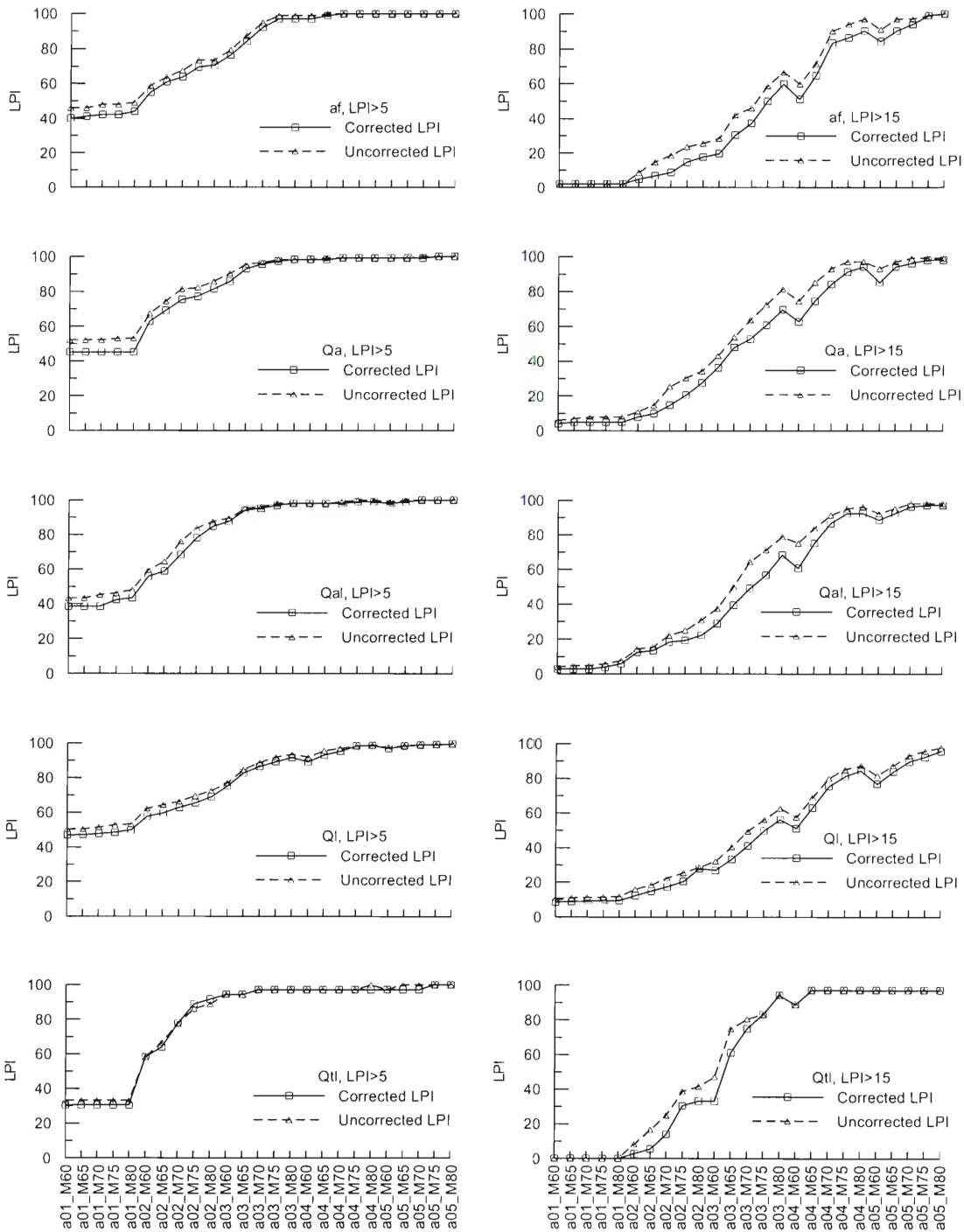


Figure 3 Comparison of LPI values with soil type assumption of sand (uncorrected) and soil type assumption based on known soil type profiles (corrected).

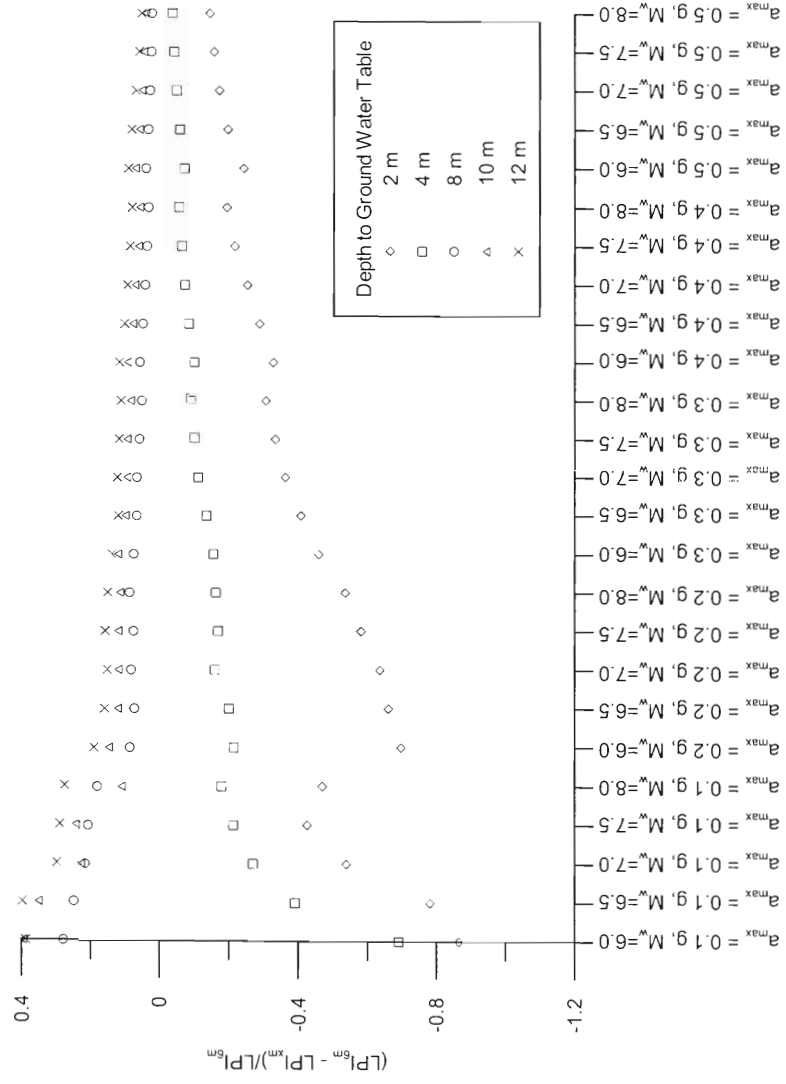


Figure 4 Effect of depth to ground water table on liquefaction potential index (LPI).

Table 3 Assumed Soil Type Profiles Based on Near-Surface Geology

<i>Depth (m)</i>	<i>af</i>	<i>Qa</i>	<i>Qal</i>	<i>Ql</i>	<i>Qtl</i>
0.6096	ML-CL	ML-CL	ML-CL	ML	ML
1.2192	ML-CL	ML-CL	ML-CL	ML	ML
1.8288	ML-CL	ML-CL	ML-CL	ML	ML
2.4384	ML-CL	ML-CL	ML-CL	ML	ML
3.048	ML-CL	ML-CL	ML-CL	ML	ML
3.6576	ML-CL	ML-CL	ML-CL	ML	ML
4.2672	ML-CL	ML-CL	ML-CL	ML	ML
4.8768	ML-CL	ML-CL	ML-CL	ML	ML
5.4864	ML-CL	ML-CL	ML-CL	ML	ML
6.096	ML-CL	ML-CL	ML-CL	ML	ML
6.7056	ML-CL	ML-CL	ML-CL	ML	ML
7.3152	ML-CL	ML-CL	ML-CL	ML	ML
7.9248	ML-CL	ML-CL	ML-CL	ML	SC
8.5344	ML-CL	ML-CL	SP	ML	SC
9.144	ML-CL	ML-CL	SP	ML	SC
9.7536	ML-CL	ML-CL	SP	ML	SC
10.3632	ML-CL	ML-CL	SP	SP	SC
10.9728	ML-CL	ML-CL	CL	SP	SC
11.5824	ML-CL	ML-CL	CL	SP	SC
12.192	SP-SM	ML-CL	SP-SM	SP	SC
12.8016	SP-SM	SP	SP-SM	SP	SC
13.4112	SP	SP	SP-SM	SP	SP
14.0208	SP	SP	SP-SM	SP	SP
14.6304	SP	SP	SP-SM	SP	SP
15.24	SP	SP	SP-SM	SP	SP
15.8496	SP	SP	SP-SM	SP	SP
16.4592	SP	SP	SP-SM	SP	SP
17.0688	SP	SP	CH	SP	SP
17.6784	SP	SP	CH	SP	SP
18.288	SP	SP	CH	SP	SP
18.8976	SP	SP	CH	SP	SP
19.5072	SP	SP	CH	SP	SP
20.1168	SP	SP	CH	SP	SP

Evaluation of fines content

The *LPI* values calculated for the SPT data were compared with the *LPI* values calculated from the CPT data. The SPT data produce significantly larger *LPI* values corresponding to a greater potential for liquefaction than the CPT data. The higher *LPI* values were partly attributed to the assumption of fines

content. The liquefaction analysis corrects SPT values to an equivalent clean sand by considering the fines content in the deposit. Based on the USCS soil type, the most conservative estimate of fines content was used. For fine-grained soils such as low-plasticity clays (CL) and low plasticity silts (ML), this approach assumes a fines content of 50%. For near surface deposits with low SPT N-values, this may produce large *LPI* values for the site. Therefore, the liquefaction severity (*S*) was set equal to 0 for deposits classified as fine-grained (ML, CL, MH, CH, ML-CL, etc.).

Figure 5a and 5b show the effect of adjusting the *LPI* to reflect the effect of fines content for an a_{max} of 0.3 g and a M_w of 6.5 and an a_{max} of 0.5 g and an M_w of 8.0. The original *LPI* is based on a fines content of 50% for soil deposits classified as fine-grained. The adjusted *LPI* assumes a severity (*S*) of 0 for soil deposits classified as fine-grained that assumes such soils do not contribute to the liquefaction susceptibility. The results show that the adjusted *LPI* values are approximately 40% of the original *LPI* for most sites evaluated.

CPT Data

California CPT Data

Liquefaction potential maps are currently being developed for the Alameda, Oakland and Piedmont, California (Holzer et al., 2002). A total of 210 CPT profiles were collected for this area by Holzer et al. (2002) as shown in Figure 6. The California data was used to validate the stochastically simulated Memphis data.

The California data was aggregated based on the surface geology of each site. Helley and Graymer (1997) produced geologic maps of Alameda County, California. These geologic maps are simplified to show the following map units: artificial fill, Holocene deposits, Holocene-Pleistocene deposits, Pleistocene deposits, and Pliocene-Pleistocene deposits. The simplified geologic map is shown in Figure 6.

Comparison with Memphis Data

The California data was analyzed to determine the *LPI* for each site and compared with the *LPI* values calculated for the Memphis data. Histograms of the *LPI* values for each geology compare the results of the Memphis data and the California data. Figures 7 and 8 show the comparison. Figure 7 compares the histograms for a moment magnitude (M_w) of 6.5 at a peak ground acceleration (a_{max}) of 0.2 g. Figure 8 compares the histograms for a M_w of 7.5 and an a_{max} of 0.4 g. For a M_w of 6.5 and an a_{max} of 0.2 g, the *LPI* results for the Memphis data show a lower variability than that observed for the California data. The *LPI* values in Memphis are low and clustered close to 0 representing little to no probability of liquefaction for a M_w of 6.5 and an a_{max} of 0.2 g. For a M_w of 7.5 and an a_{max} of 0.4 g, the variability in *LPI* for the Memphis data is still less than that observed for the California data. The profiles in Pleistocene regions in Memphis show a larger variability in calculated *LPI* than that observed in California. The CPT profiles used to generate simulated profiles in this geology are based on two locations that are more than 20 km apart. This creates a bimodal distribution in *LPI* values and increases the observed variability. In contrast, the CPT profiles in Pliocene-Pleistocene regions in Memphis show little variability in the calculated *LPI* since only two CPT profiles are available for this geologic region.

The comparison of *LPI* variability between the Memphis data and the California data provide a method of validating the statistics used in the stochastic simulation. In particular, the variability or standard deviation of the California data may be used in the simulation of profiles in the Memphis area to better approximate the variability observed.

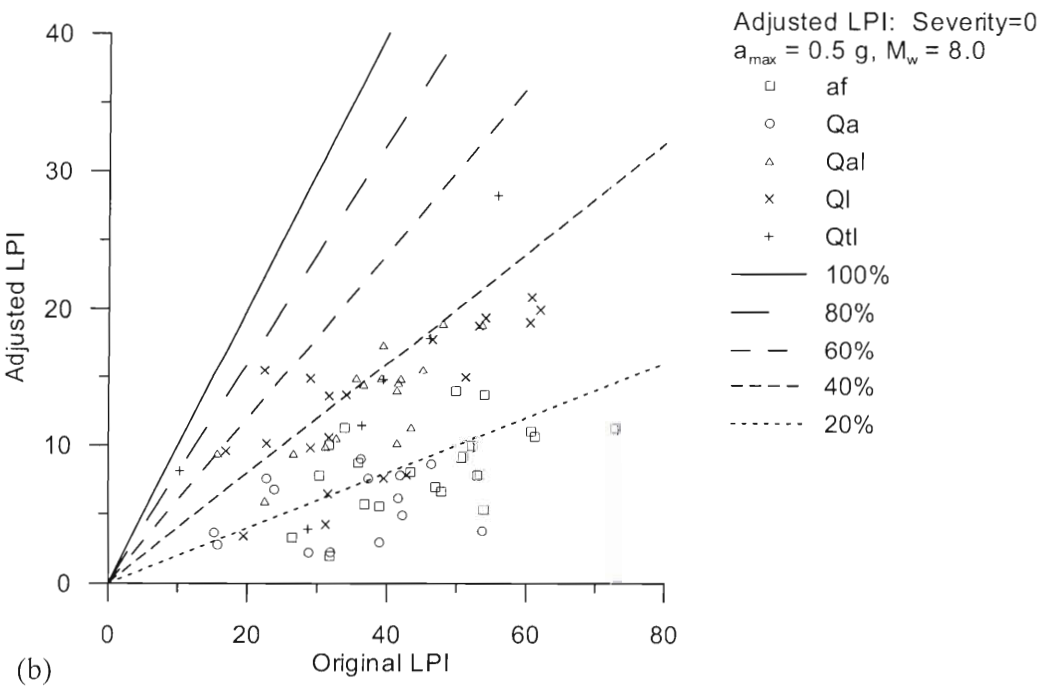
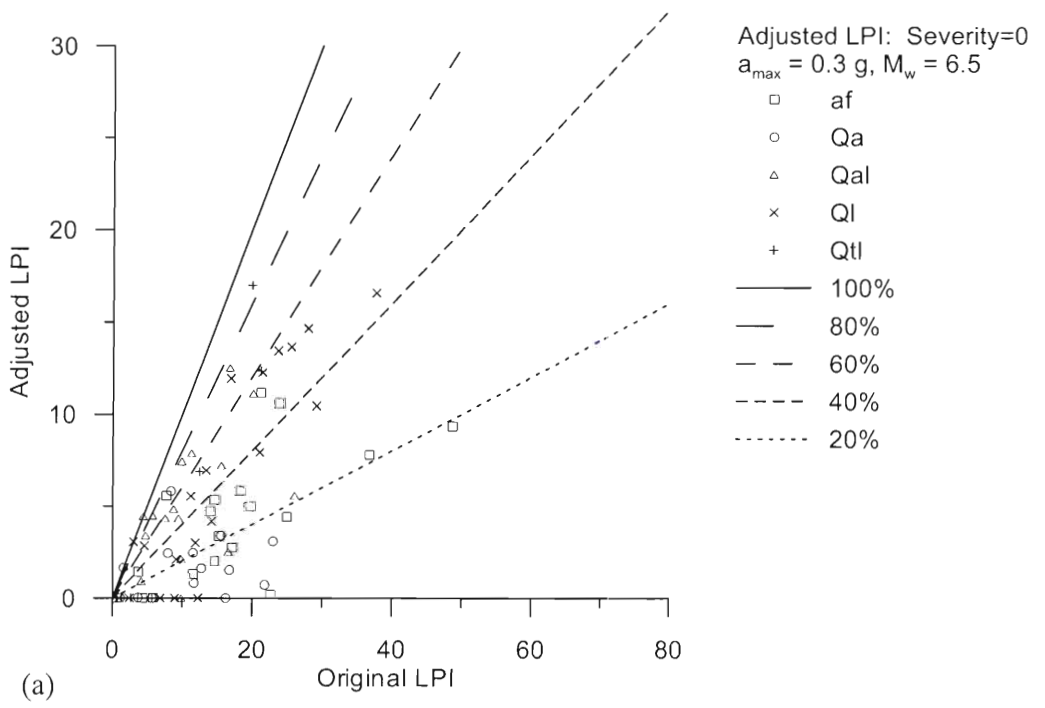


Figure 5 Effect of fines content for (a) a_{max} of 0.3 g and M_w of 6.5 and (b) for a_{max} of 0.5 g and M_w of 8.0. Unadjusted LPI based on fines content of 50% for fine-grained soils (ML, CL, CH, MH, etc.). Adjusted LPI assumes liquefaction severity is 0 for fine-grained soils.

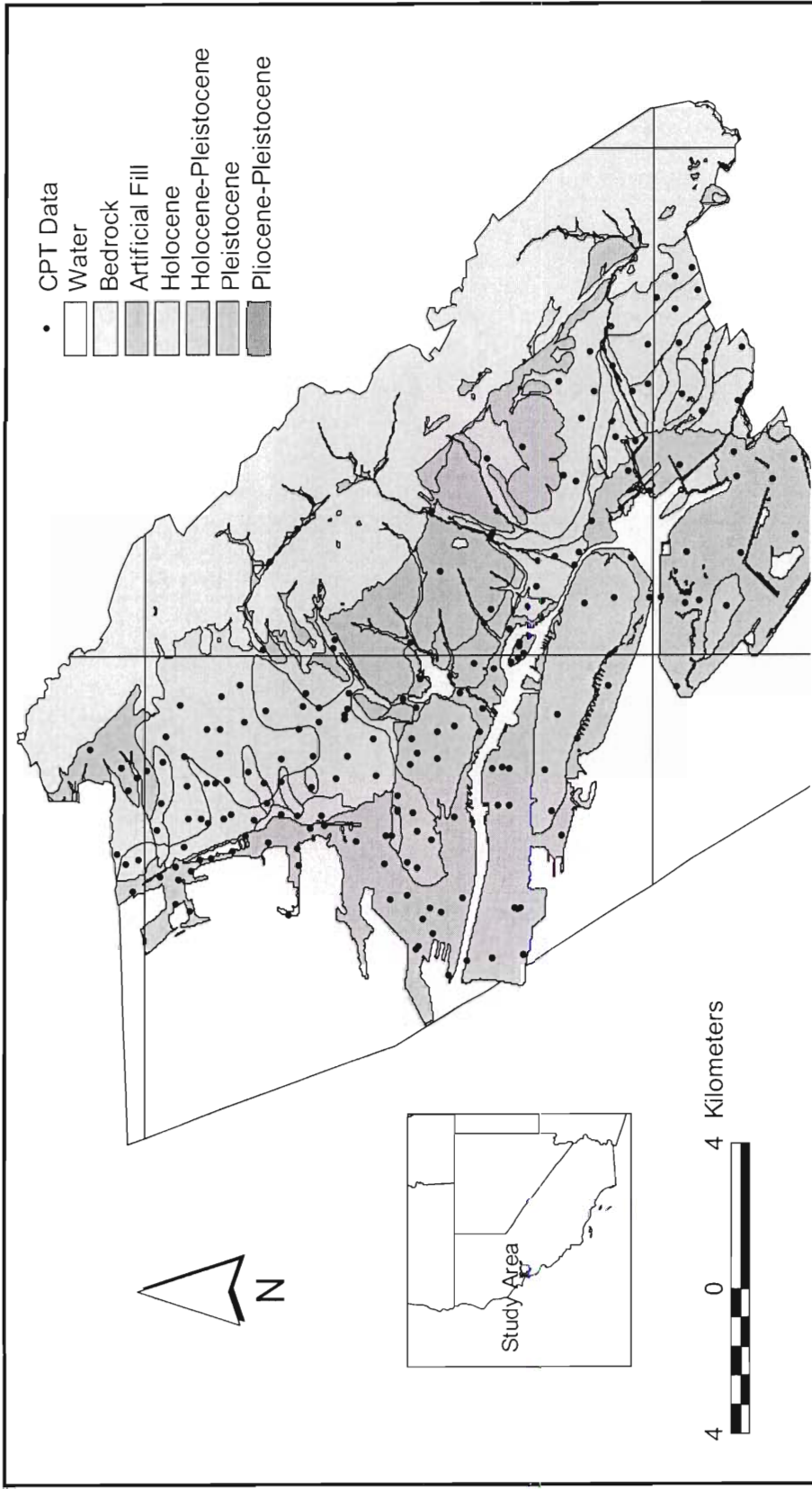


Figure 6 Near-surface geology of Alameda, Oakland, and Piedmont, California and location of CPT sites.

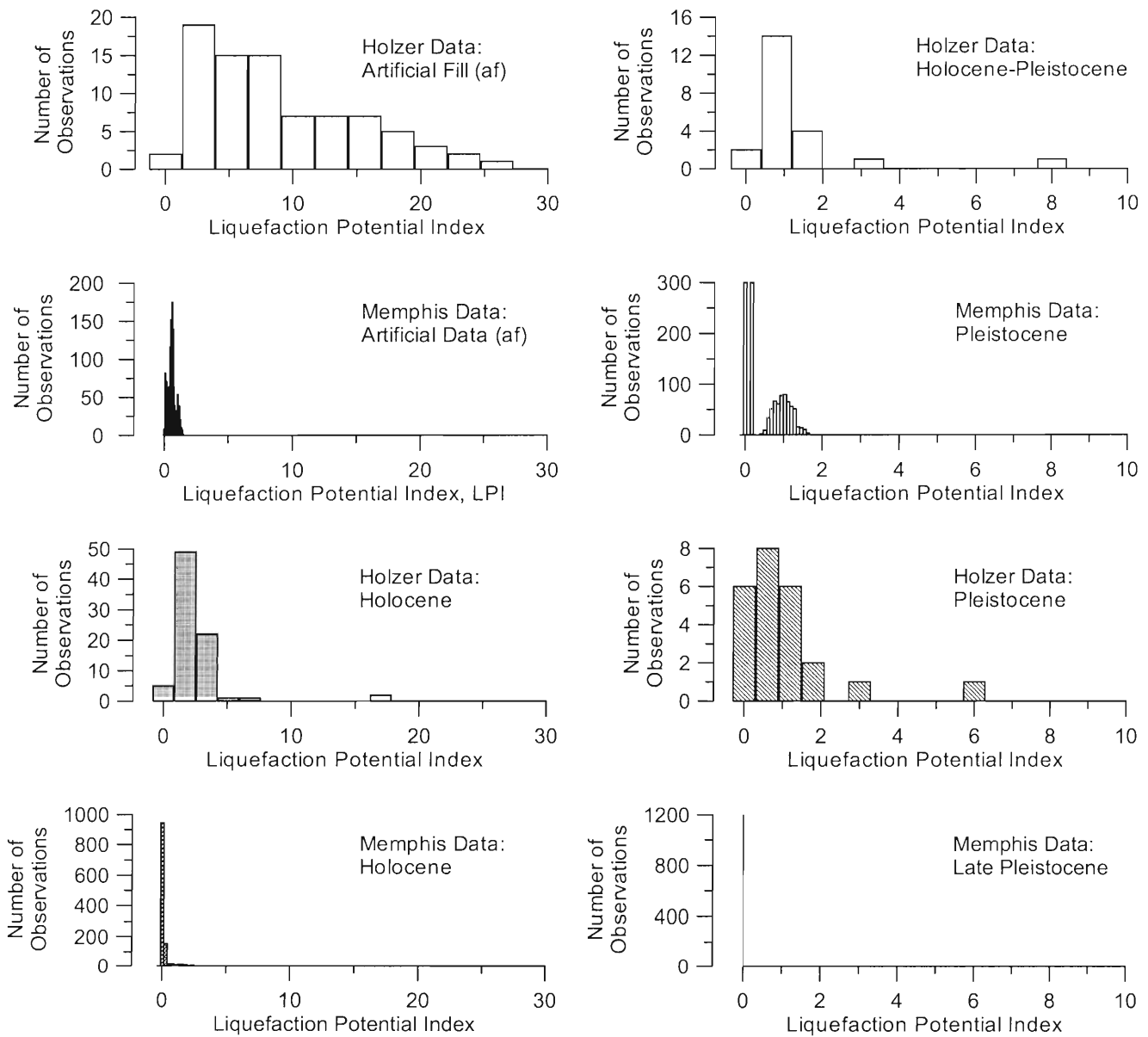


Figure 7 Comparison of histograms of liquefaction potential index (*LPI*) of California (Holzer data) data and Memphis data for a M_w of 6.5 and an a_{max} of 0.2 g.

Further Studies

There are four main tasks to complete the project:

Task 1 – CPT Analysis

Based on the validation analysis, the stochastic simulation is not able to adequately capture the variability observed in situ due to the limited CPT profiles available. Therefore, the analysis of CPT profiles will be based on the mean of the Memphis CPT profiles and the variability calculated from the California CPT profiles.

Task 2 – Merging of CPT and SPT-Based Maps

The final liquefaction hazard maps will be based on both the CPT and SPT data. This involves combining results from a method that utilizes a limited quantity of high-quality CPT data with a method that utilizes a large quantity of lower quality SPT data. The simplest approach is to weight each result equally when combining them to prepare the final maps, but other combinations will also be considered based on input from the USGS and other experts.

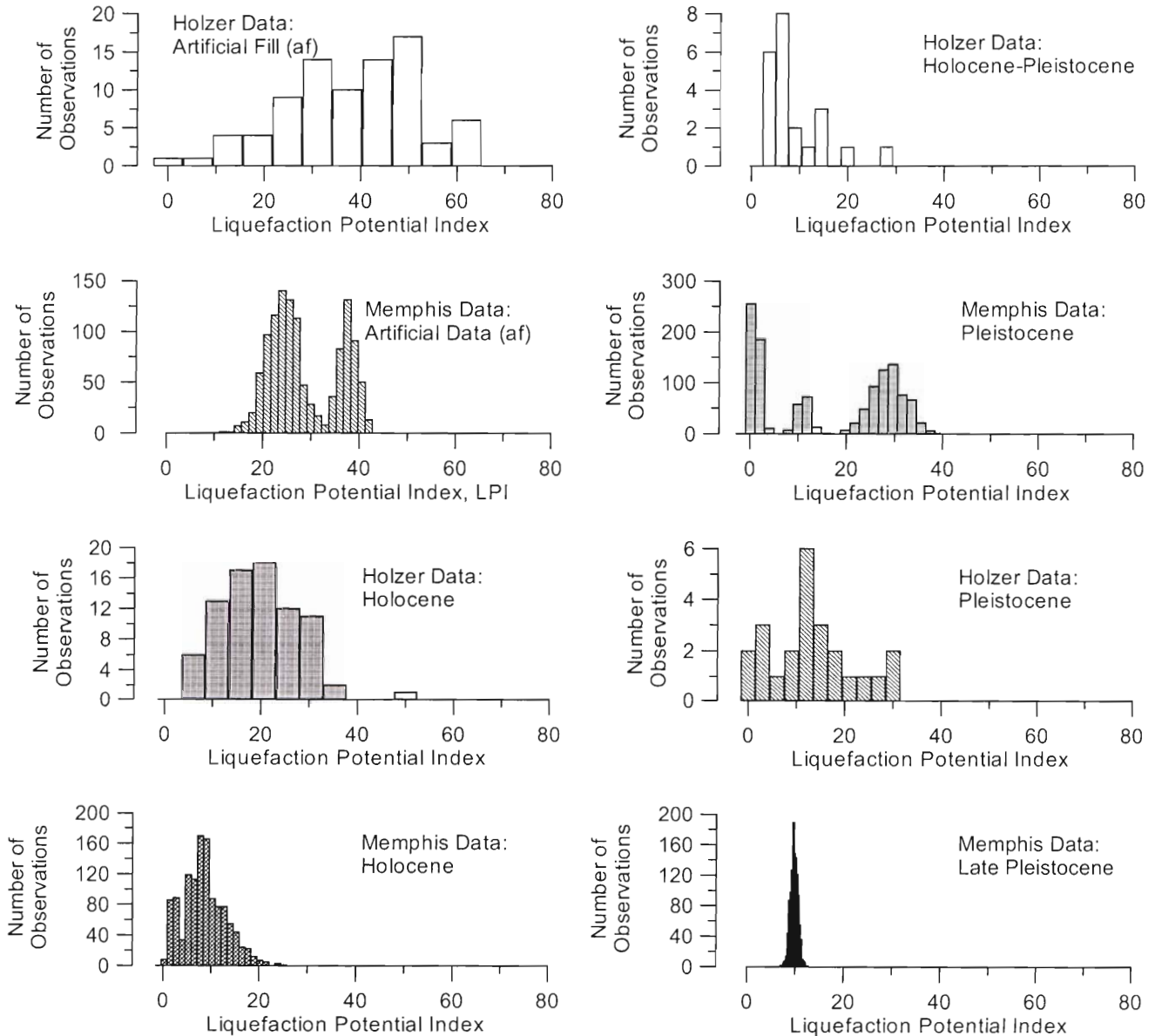


Figure 8 Comparison of histograms of liquefaction potential index (*LPI*) of California (Holzer data) data and Memphis data for a M_w of 7.5 and an a_{max} of 0.4 g.

Data Availability Statement

The CPT data compiled is available for distribution from the author. The groundwater table data is available at the website <http://waterdata.usgs.gov/nwis>.

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