Search Main Menu

GEOSTATISTICAL ANALYSIS OF LIQUEFACTION INDUCED GROUND RESPONSE AT THE MARINA DISTRICT

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Abstract

Soil spatial variability can have a profound effect on its behavior under earthquake loading. In this study, the seismic response of the Marina District, California, during the Loma Prieta earthquake (1989) was analysed to quantify the effect of soil spatial variability on liquefaction assessment. Cone penetration test (CPT) data were used to identify different lithologies at the site. For each lithology, CPT tip resistance data were treated as a random variable and were used to estimate different elements of soil spatial variability. Monte Carlo simulation was used to obtain different realizations of CPT data. These realizations were then implemented into empirical approaches to examine liquefaction susceptibility expressed in terms of the factor of safety against cyclic liquefaction in a probabilistic analysis framework. In addition, stochastic analyses of liquefaction-induced surface damage were carried out by implementing the CPT realizations into liquefaction settlement criteria.

1. INTRODUCTION

Most soils are heterogeneous in nature either due to the presence of different lithologies or as a result of their inherent spatial variability. Soil spatial variability can have a profound effect on ground response under earthquake loading, as discussed by Fenton and Vanmarcke (1991), Popescu et al (1998), and Elkateb et al. (2003b and 2003c). Quantitative treatment of this variability is important, as classical deterministic analyses can not account for the scatter of field data and their spatial correlation. Well-documented case histories provide an opportunity to explore options for quantifying the effect of soil spatial variability on liquefaction-induced ground response. A good example of this type of case histories is the Marina District site, California, where different signs of liquefaction, such as sand boils, lateral spreads, building destruction and surface settlements, were recorded during the 1989 Loma Prieta earthquake.

Several studies have been carried out to investigate the ground response at the Marina District during the 1989 Loma Prieta earthquake in a deterministic fashion making it one of the most comprehensively studied liquefaction case histories. Examples of these studies are O'Rourke and Pease (1997 and 1992), and Bardet and Kapuskar (1993).

To the authors' knowledge, the only attempt made to quantify the effect of spatial variability of soil properties at the Marina District on its seismic response was that of Rollins and McHood (1998). The mean plus/minus the standard deviation of the Standard Penetration Test results were implemented in Tokimatsu and Seed (1987) empirical settlement approach to obtain a risk-based estimate of the range of expected settlement at the site. A reasonable agreement was obtained between the predicted and recorded settlements. However, this was not done in a probabilistic framework and, as a result, the effect of extreme value statistics was not accounted for. In addition, the spatial correlation between soil properties and its implications on expected settlement was not taken into consideration.

In this study, a geostatistical approach was adopted to assess the effect of spatial variability of soil properties on the ground response during the 1989 Loma Prieta earthquake. Cone Penetration Test results were used to identify different ground lithologies (soil behaviour types) implementing the soil behaviour type index, I_c, (Robertson 1990). Different geostatistical characteristics, such as mean, variance, and spatial correlation structures, were estimated for each of these lithologies. The CSR-CRR approach (Robertson and Wride 1998) was employed stochastically to estimate the liquefaction susceptibility of the ground, expressed in terms of the factor of safety against cyclic liquefaction. This was carried out by implementing Monte Carlo simulation techniques to obtain several realizations of the CPT data, which were then used to estimate the value of the cyclic resistance ratio (CRR). On the other hand, the earthquake loading was assessed deterministically using simplified techniques that correlated the cyclic stress ratio (CSR) to the earthquake magnitude and the maximum surface acceleration recorded at the site. In addition, stochastic settlement analyses were carried out to assess the influence of soil spatial variability on liquefaction-induces settlement.

2. BACKGROUND ON THE MARINA DISTRICT

The Marina District is located on the north end of San Francisco at a distance of 107 km from the epicentre of the Loma Prieta earthquake. The geology of the site has been described by many authors, such as Rollins and McHood (1998), based on the results of extensive field investigation program. The upper-most layer, which extends to a depth of 4 to 7 m below ground surface, can be divided into 3 distinct units, as shown in Figure 1, which are:

1. Natural beach and sand bar deposits associated with the original shoreline of San Francisco Bay in 1857 (section C);

2. Land and barge tipped sand fill, which was backfilled in the site as a part of the construction of a seawall and an earthen mole between 1857 and 1912 (section B); and
3. Hydraulic fill, mostly sand with some zones of fine-grained soils, which was obtained from several borrow pits in San Francisco Bay and dumped in the lagoon enclosed by the seawall as a part of reclamation projects in preparation for the 1915 Panama Pacific International Exhibition (section A).

Different units of surface layers are underlain by soft to medium clay (Holocene bay mud) to a depth ranging from 11 to 14 m followed by a dense cemented sand (hardpan) to depth of 22 to 25 m. The sand is underlain by stiff clay (Pleistocene bay mud) to a depth of 74 to 77 m followed by bedrock. The ground water table (GWT) is found at a depth of 2.4 m below ground surface in the flat area immediately to the south of San Francisco Bay.

The Loma Prieta earthquake (Richter magnitude of 7) hit the Marina District in 1989 causing a devastating damage, where 10 people died and another 40 were injured together with the destruction of more than 40 houses. Different signs of liquefaction were recorded at the site during the earthquake in the form of buckling of sidewalks, tension cracks and more than 74 sand boils. Almost all of these damages were restricted to the hydraulic fill area (section A) except for the buckling of two side walks in section C, which is thought to be a result of lateral spreads of liquefied layers in section A. The most severe structural damage occurred at the boundary between the hydraulic fill and other units as a result of considerable differential settlement. In addition, lateral spreads up to 30 cm and vertical settlements more than 12.5 cm were recorded in section A, compared with negligible lateral spreads and settlements less than 2.5 cm in section C. Based on the field observations, the authors believe that only section A of the Marina District liquefied during the Loma Prieta earthquake.

It should be noted that there was no records of the ground acceleration are available for the Marina District during the Loma Prieta earthquake. However, several records of bedrock and surface acceleration were recorded at different locations in the vicinity of the Marina District. These records were used to obtain the design maximum surface acceleration used in the current study as illustrated in the subsequent sections.

3. CHARACTERIZATION OF GROUND HETEROGENEITY

The area under investigation in this study is bounded to the north, south, east and west by the Martina Boulevard, Francisco, Fillmore and Baker Streets, respectively. Only the area underlain by hydraulic fill (section A) and that underlain by natural deposits (section C) were considered in this study where a reasonable number of CPT soundings were available as shown in Figure 1.

Characterization of ground heterogeneity in these two areas was done in three main stages. In the first stage, standardization and filtration procedures were applied to CPT data. In the second stage, geostatistical characteristics of the standardized data were obtained. Finally, stochastic simulation of the standardized data was performed in the third stage.

Details of these stages are discussed in the following sections

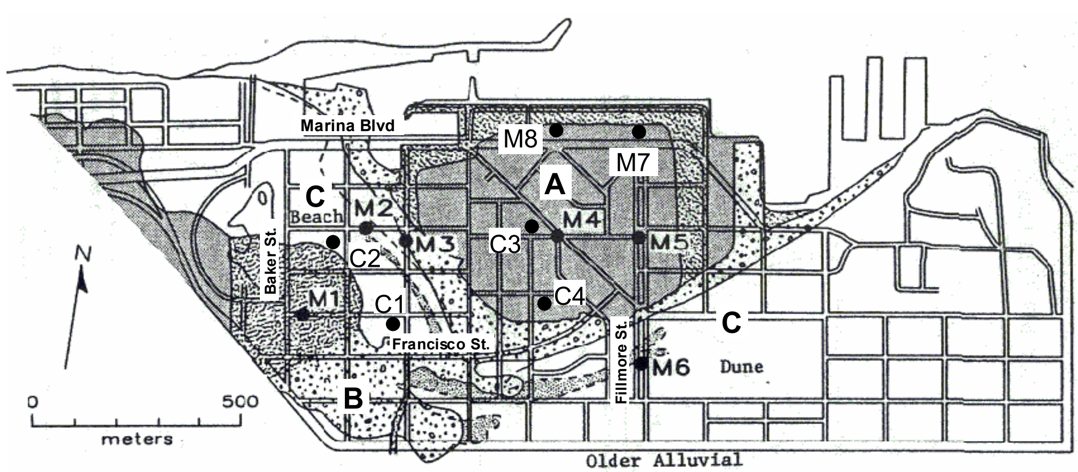

Figure 1. Layout of CPT data locations at the marina District (A: sections underlain by hydraulic fill, B: sections underlain by dumped fill, and C: sections underlain by natural ground). modified from Bennett (1990).

3.1 Standardizing Cone Penetration Test Data

The results of several cone penetration tests soundings, shown in Figure 1, were used to characterize the spatial variation of soil properties for sections A and C of the Marina District. These CPT sounding were conducted by the United States Geological Survey (USGS), denoted by M1 to M8, and by the University of Southern California, denoted by C1 to C4. The cone data were used to identify different ground lithologies (soil layers) using the soil behaviour type index, I_c, (Robertson 1990) resulting in a detailed west-east longitudinal ground profile, as shown in Figure 2. Four cohesionless soil layers below GWT, L_{1A}, L_{2A}, L_{3A} and L_{4A}, were considered as potentially liquefiable zones for section A. Similarly, four layers, L_{1B}, L_{2B}, L_{3B}, and L_{4B}, were identified as potentially liquefiable zones for section C. Each of these layers was considered as a statistically homogeneous domain, where cone tip resistance, q_c, was treated as a random variable. On the other hand, cohesive soils associated with $I_c > 2.6$, denoted by soil behaviour types 2, 3, and 4, were assumed to be non-liquefiable layers (Robertson and Wride 1998).

Data filtration is an important process where outliers are identified and excluded from field data to maintain statistical consistency. Outliers can be manifested in the form of spikes in CPT profiles at certain depths, as the soil being tested may include anomalies in the form of very thin lenses of clay or sand, or pockets of gravel. In this study, data filtration was carried out following the procedure proposed by Elkateb et al. (2003b).

A necessary condition for stochastic analyses is stationarity, which implies that the mean and variance of random variables are constants across the analysis domain. It can be expected, however, that CPT data will exhibit vertical trends due to their sensitivity to changes in effective confining pressure. In order to use cone tip resistance, q_c, as a random variable and meet the stationarity condition, any possible vertical trend in q_c should be removed (detrended). To achieve this, filtered data from all CPT soundings were utilized to identify deterministic linear vertical trends in q_c within each of the potentially liquefiable layers using linear regression analysis. Then, these trends were removed producing detrended cone tip resistance data through the relation:

$$q = q_c - q_o(z) \qquad [1]$$

where q is the detrended cone tip resistance and q_o (z) is the deterministic vertical trend.

3.2 Geostatistical Properties of Detrended CPT Data

To proceed with stochastic analyses, geostatistical characteristics of random variables, such as mean, variance, probability distribution and correlation structure, have to be determined. A summary of the geostatistical characteristics of detrended CPT tip resistance data for different potentially liquefiable layers is presented in Table 1. The mean values were found to be around zero, as expected, whereas the standard deviations ranged from 380 kPa to 4420 kPa. The probability distributions were in close agreement with normal distributions for all of the potentially liquefiable layers, as deduced from Q-Q plots (Deutsch 2002). Details of the use of Q-Q plots to assess the probability distribution type of field data is beyond the scope of this paper and can be found elsewhere, e.g. Elkateb et al. (2003b).

Soil properties do not vary randomly in space; rather such variation is gradual and follows a pattern that can be quantified using what is called spatial correlation structure. In this study, variogram functions (Deutsch 2002) were adopted as measures of quantifying spatial correlation between detrended CPT data. The GSLIB Geostatistical Software Library (Deutsch and Journel 1998) was used to obtain variogram characteristics, such as the model and spatial range, in the vertical direction for each of the potentially liquefiable layers, as shown in Table 1. It should be noted that insufficient data was available to quantify the variogram characteristics of layers L_{3A}, L_{3B} and L_{4B}. As a result, it was assumed that layer L_{3A} had the same variogram characteristics as layer L_{2A} and that layers L_{3B} and L_{4B} had variogram characteristics similar to layer L_{2B}.

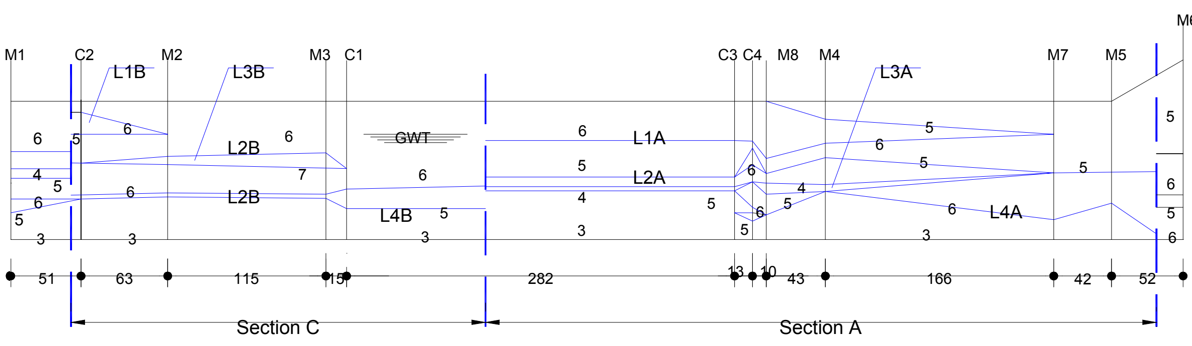

Figure 2. A longitudinal west-east view showing the lithological distribution across the Marina District (positions of CPT soundings are shown in Figure 1; numbers represent soil behavior type based on soil behavior type index I_c).

Table 1. Statistical properties of detrended CPT tip resistance for different layers

Layer	Mean (kPa)	Standard Deviation (kPa)	Variogram Characteristics		
			Model	Range (m)	
				Vertical	Horizontal
L_{1A}	0.038	862	Exp.*	0.65	11.05
L_{2A}	0.004	444	Gaus*	0.80	13.6
L_{3A}	-0.23	380	Gaus*	0.80	13.6
L_{4A}	0.003	1466	Sph.*	1.40	23.8
L_{1B}	-0.12	585	Exp.*	0.75	12.75
L_{2B}	-0.07	4418	Exp.*	2.15	36.55
L_{3B}	0.161	1938	Exp.*	2.15	36.55
L_{4B}	0.049	668	Exp.*	2.15	36.55

* Exp. = exponential, Gaus. = Gaussian, and Sph. = spherical

One limiting boundary condition required to use GSLIB to obtain variogram characteristics is that each of the layers considered has to be rectangular in shape. Consequently, a coordinate transformation process was carried out following the procedure of Elkateb et al. (2003b) producing transformed idealized rectangular profiles for the potentially liquefiable layers. These transformed sections are amenable to analysis within the GSLIB and retain the actual spatial continuity of field data. Details of this transformation process are beyond the scope of this paper and can be found elsewhere, e.g. Deutsch (2002).

3.3 Stochastic Simulation of Detrended CPT Data

To quantify the effect of soil spatial variability, several realizations of detrended CPT data were obtained for each of the potentially liquefiable layers. This was carried out implementing Monte Carlo simulation using the @Risk software (Palisade Corporation 1996). The number of realizations used in the analysis, about 10,000, was assessed by specifying an acceptable tolerance of 0.50% between the input distributions and the distributions of the sampled valued obtained from Monte Carlo simulation.

It should be emphasized that the variance used in the simulation process was not the point variance of field data, shown in Table 1. Rather, it was the variance of the spatial average of CPT data over a certain volume. These spatial averages typically have narrower probability distributions than point statistics and consequently smaller variances (Vanmarcke 1977). The variance of these spatial averages was correlated to the point variance using a variance reduction factor (Vanmarcke 1984) through the relationship:

$$(\sigma)_{\Gamma} = \Gamma_{v} \times \sigma \qquad [2]$$

where: σ is the standard deviation;
σ_{Γ} is the standard deviation of the spatial average of data over volume v; and
Γ_{v} is the square root of the variance reduction factor.

The variance reduction factor depends on the averaging volume, type of correlation structure, and the limit of spatial correlation between field data. Several analytical expressions for the variance reduction factor can be found in the geotechnical literature, e.g. Vanmarcke (1984) and Elkateb et al. (2003a). It was assumed in this study that the variance reduction factor would be affected only by the size of the averaging volume in the vertical direction, i.e. layer thickness. This was attributed to the fact that averaging volumes in the horizontal direction are generally small compared to the horizontal limit of spatial correlation resulting in variance reduction factors very close to unity (Elkateb et al. 2003b). It is worth noting that the thicknesses of the potentially liquefiable layers were not uniform across the analysis domain. As a result, an average thickness was obtained for each layer, following the procedure of Elkateb et al. (2003b), which was employed to obtain the variance reduction factors presented in Table 2. These average thicknesses were divided into horizontal sublayers, as shown in Table 2, to maintain a minimum value of 0.70 for the variance reduction factor, as recommended by Deutsch (2002) to ensure high accuracy upon applying Equation 2. It should be emphasized that the outcomes of applying Monte Carlo simulation to these sublayers were not independent due to the vertical correlation between the data in these sublayers. The effect of such correlation was accounted for through implementing a correlation coefficient between the spatial averages of CPT data over these sublayers into the simulation process (Elkateb et al. 2003b).

Table 2. Variance reduction factor for different potentially liquefiable layers at the Marina District

Layer	L_{1A}	L_{2A}	L_{3A}	L_{4A}	L_{1B}	L_{2B}	L_{3B}	L_{4B}
Average thickness (m)	0.92	1.77	0.59	1.63	0.45	1.80	0.85	0.58
Number of horizontal segments	4	3	1	2	2	3	1	1
Variance reduction factor	0.72	0.80	0.80	0.72	0.76	0.77	0.70	0.78

4. STOCHASTIC ANALYSIS OF LIQUEFACTION SUSCEPTIBILITY

Stochastic analysis of liquefaction susceptibility of the ground at the Marina District was performed by applying a deterministic empirical approach to different realizations of the retrended cone tip resistance data (Elkateb et al. 2003b). The CPT-based empirical approach of Robertson and Wride (1998) was used to correlate the cyclic resistance ratio (CRR) to the retrended CPT data. The retrended data were obtained by adding back the linear deterministic trends to the realizations of detrended CPT tip resistance obtained from Monte Carlo simulations. The cyclic stress ratio (CSR) was assessed deterministically from the earthquake magnitude and the maximum surface acceleration using the simplified approach of Seed and Idriss (1971). The factor of safety against liquefaction was obtained through the relationship:

$$F.S = \frac{CRR}{CSR} \qquad [3]$$

It should be noted that the maximum surface acceleration was not recorded at the Marina district. However, several accelerogram records on bedrock were obtained at several locations in the vicinity of the Marina District, where the horizontal acceleration ranged between 0.05g and 0.11g, as shown in Table 3.

Table 3. A summary of recorded maximum accelerations on bedrock at different locations in the vicinity of the Marina District

Location	Distance* (km)	Max. recorded acceleration (g)
Rincon Hill	4.90	0.09
Pacific Heights	1.70	0.05
Telegraph Hill	2.70	0.08
Cliff House	6.70	0.11
Yerba Buena Island	7.00	0.06

* from the center of Marina District

The maximum ground acceleration on bedrock at the Marina District was estimated as the weighted average of the maximum surface acceleration recorded at these locations, and was found to be around 0.065g. The weights used in the determination of this weighted average acceleration were considered to be inversely proportional to the distance between the location of the recorded acceleration and the Marina District. The estimated maximum ground acceleration on bedrock together with the design charts of Idriss (1990) and Seed et al. (1994) were used to estimate a maximum surface acceleration of 0.17g at the Marina District. These design charts were developed to take into account the effect of local site conditions on the amplification of ground accelerations on bedrock.

Due to the stochastic nature of the CRR, applying Equation 3 resulted in histograms of the factors of safety for each of the potentially liquefiable layers, as shown in Figure 3 for layer L_{1A}. A summary of the statistical characteristics of the factor of safety against cyclic liquefaction is presented in Table 4. The mean factors of safety were found to range between 0.74 and 1.17 for section A, and between 1.03 and 14.26 section C. The coefficients of variation, COV, were assessed to range between 0.05 and 0.16 for section A, and between 0.14 and 0.53 for section C. The probabilities of failure (factor of safety less than unity) were found to range between 19.81% and 100% for section A, and between 0.01% and 46.92% for section C.

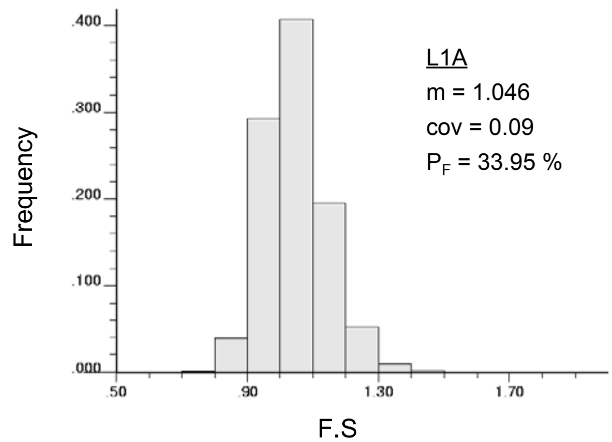

Figure 3. Histograms of the factor of safety against liquefaction for layer L_{1A}

Embedment depths and thickness of potentially liquefiable layers play an important role in liquefaction potential. Two layers with the same probability of failure may have different impact on liquefaction potential if they are at different depths or if they are of different thickness. As a result, Elkateb et al. (2002b) developed an estimate of equivalent failure probability that took into consideration the effect of the thickness and embedment depth of different layers on the probability of failure in the form:

$$P = \sum_{i=1}^{n} P_{Fi} \cdot \frac{T_i / Z_i}{\sum T_i / Z_i} \qquad [4]$$

where : P is the equivalent failure probability of the site;
P_{Fi} is the probability of failure of layer i;
T_i and is the average thickness of layer i; and
Z_i is the vertical distance from ground surface to the center of layer i.

Table 4. A summary of the statistical characteristics of the factor of safety against cyclic liquefaction for different potentially liquefiable layers.

Layer	L_{1A}	L_{2A}	L_{3A}	L_{4A}	L_{1B}	L_{2B}	L_{3B}	L_{4B}
Mean factor of safety	1.05	0.84	0.74	1.17	1.48	5.46	14.26	1.03
Coefficient of variation	0.09	0.06	0.05	0.16	0.14	0.53	0.22	0.16
Probability of failure (%)	33.95	99.86	100	19.81	1.13	5.20	< 0.01	46.92

The equivalent failure probability for Section A, where different signs of liquefaction were recorded during the Loma Prieta earthquake, was found to be 63.5%. This is in agreement with the findings of Elkateb et al. (2003c), which identified a critical threshold range of 1.2% to 11.9% for the equivalent failure probability above which liquefaction is likely to occur. On the other hand, an equivalent failure probability of 6.5% was assessed for Section C, where no sign of liquefaction was encountered. This implied that the critical threshold for the equivalent failure probability could be refined to a range of 6.5% to 11.9%, but continued analysis of liquefaction case histories is required to refine the selection of this value.

5. STOCHASTIC ASSESSMENT OF LIQUEFACTION-INDUCED SETTLEMENT

The 10,000 realizations of retrended CPT data, used in the previous section, were implemented in Ishihara's empirical approach (1993) to assess liquefaction-induced settlement at the Marina District under the effect of the Loma Prieta earthquake in a stochastic fashion. This resulted in obtaining a histogram of predicted settlements at the location of each CPT sounding. The mean settlements across the site were found to range from 10.5 cm to 19.1 cm for section A, and from 1.4 cm to 3.8 cm for section C. The coefficients of variation were assessed to range from 0.05 to 0.28 for the section A, and from 0.71 to 1.21 for section C. The stochastic analyses results were used to generate contours of the mean settlements across the site, as shown in Figure 4.

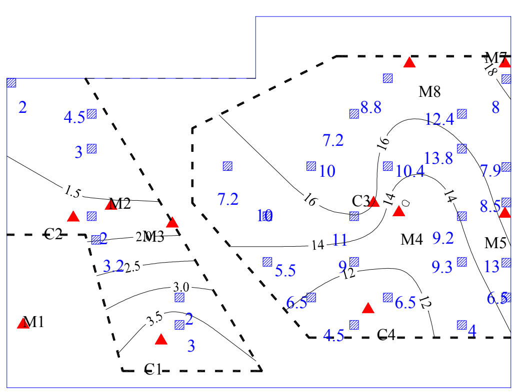

Figure 4. A site plan showing contours of computed mean settlements (in cm) across the Marina District

In addition, the readings of several settlement points at the site during the Loma Prieta earthquake were located on the contour lines as indicated by the hatched squares in Figure 4. The recorded settlements were found to be greater than the computed mean values at some settlement points, especially in section C. This implied that the use of mean values in liquefaction-induced settlement analysis could be on the unsafe side. This can be attributed to the presence of loose pockets resulting in low factors of safety and higher settlements, which can not be accounted for using the classical deterministic analyses using mean values.

Alternatively, settlements associated with the upper and lower limits of the 90% confidence level were determined as risk-based estimates of liquefaction-induced settlement as proposed by Elkateb et al. (2003b). Using these estimates in settlement assessment implies that there is only a 5% chance of having actual settlement either greater than the upper limit or smaller than the lower limit. Contours of settlements associated with the 90% confidence level were generated across the Marina District, as shown in Figure 5. It is worth noting that some recorded settlements were smaller than those associated with the lower limit of the 90% confidence level. However, the use of these estimates in previous case histories was found to provide a wide range of predicted settlement (Elkateb et al. 2003b and 2003c), which was considered to be on the over-conservative side. This paradox can be attributed to the following:

1. The uncertainty in the maximum surface acceleration at the Marina District. It is the authors' opinion that the used acceleration was over-estimated and greater than the actual acceleration that hit the site during the Loma Prieta earthquake. This can be overcome through performing a comprehensive probabilistic analysis that takes into consideration the uncertainty in ground acceleration;
2. The number of CPT sounding could be considered insufficient to perform reliable probabilistic analysis of liquefaction-induced settlement;
3. The poor distribution of the CPT soundings across the site, where large zones of the potentially liquefiable layers were not covered by CPT soundings; and
4. The CPT soundings conducted by the University of Southern California, soundings C1 to C4, had cone tip resistance data at 0.30 m interval, which might be considered inadequate to perform a reliable quantification of some elements of soil spatial variability. This was manifested in assuming the

model type and the spatial range of layers L_{3A}, L_{3B} and L_{4B}.

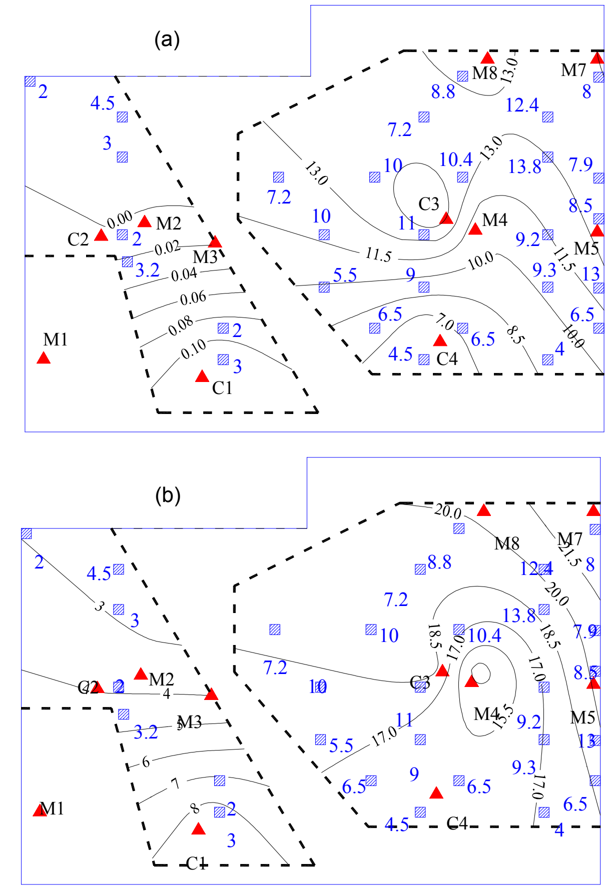

Figure 5. A site plan showing contours of computed settlements (in cm) across the Marina District under the effect of the Loma Prieta earthquake, a) lower limit of 90% confidence interval, b) upper limit of 90% confidence interval.

Ishihara and Yoshimine (1992) proposed a liquefaction damage criterion where surface damage was correlated to ground settlement. It was suggested that significant surface damage was usually associated with a ground settlement of 10 cm or more. In order to apply this damage criterion, the stochastic settlement analyses results were used to assess the probability of occurrence of liquefaction-induced settlement greater than 10 cm, a value considered to be associated with significant surface damage. Contours of these probabilities were generated across the Marina District, as presented in Figure 6. This figure verified the findings of Elkateb et al. (2003b), where zones of surface damage were suggested to be correlated with a 12% probability, or more, of occurrence of settlement larger than 10 cm. It should be emphasized that the buckling of side walks encountered at Section C were likely a result of lateral spread of the liquefied section A rather than a manifestation of liquefaction of underlying liquefiable layers.

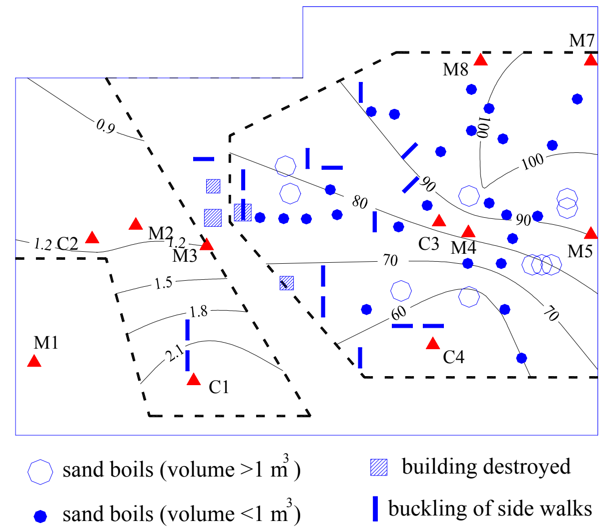

Figure 6. A site plan showing contours of probability of occurrence of liquefaction-induced settlement greater than 10 cm.

6. CONCLUSIONS

In this study, a geostatistical approach was adopted to assess the effect of spatial variability of soil properties on earthquake-induced ground response at the Marina District during the 1989 Loma Prieta earthquake. Cone Penetration Test results were used to identify different ground lithologies and their geostatistical characteristics, such as the mean, variance, and spatial correlation structures. The (CSR-CRR) approach (Robertson and Wride 1998) was employed stochastically to estimate the liquefaction susceptibility of the ground, expressed in terms of the factor of safety against cyclic liquefaction. In addition, stochastic settlement analyses were carried out to assess the influence of soil spatial variability on liquefaction-induces settlement and to examine damage criteria developed in previous liquefaction studies.

This study verified the applicability of the equivalent failure probability approach for liquefaction prediction. This approach was developed by Elkateb et al. (2003b) to account for the effect of thickness and embedment depth of potentially liquefiable layers on their failure probabilities and its implications on the site susceptibility to liquefaction. The outcomes of this study were used to refine the critical threshold of the equivalent failure probability to be in the range of 6.5% and 11.9%, rather than the 1.2% to 11.9% range obtained from the analysis of the Treasure Island (Elkateb et al. 2003c). Liquefaction occurrence is likely to be correlated to equivalent failure probabilities greater than such critical threshold. However, care should be taken while using this threshold due to the uncertainty associated with the maximum surface acceleration at the Marina District. This uncertainty was manifested in recorded settlement outside the predicted range of settlement associated with the upper and lower limit of the 90% confidence level. This implies that such uncertainty is likely to have a profound effect on the methodology applied in this study. This can be overcome by performing comprehensive probabilistic analysis that takes into consideration the uncertainty in earthquake loading.

The findings of this study are in agreement with that of the Wildlife site (Elkateb et al. 2003b), where zones of liquefaction-induced surface damage were considered to be associated with a 12% probability, or higher, that liquefaction-induced settlement will be greater than 10 cm.

7. REFERENCES

Bardet J. P. and Kapuskar, M. 1993. Liquefaction sand boils in San Francisco during the 1989 Loma Prieta earthquake. Journal of the Geotechnical Engineering Division, ASCE, 119, GT(3): 543-562.

Deutsch, C. V. 2002. Geostatisitical reservoir modeling. Oxford University press.

Deutsch, C. V. and Journel, A. G. 1998. GSLIB geostatistical software library. Oxford University press.

Elkateb, T., Chalaturnyk, R., and Robertson, P. K. 2003a. An overview of soil heterogeneity: quantification and implications on geotechnical field problems. Canadian Geotechnical Journal, 40 (1): 1-15.

Elkateb, T., Chalaturnyk, R., and Robertson, P. K. 2003b. Simplified geostatistical analysis of earthquake induced ground response at Wildlife site. Canadian Geotechnical Journal, 40 (1): 16-35.

Elkateb, T., Chalaturnyk, R., and Robertson, P. K. 2003c. Stochastic liquefaction induced ground response at the Treasure Island. Paper submitted to the Journal of Geotechnical and Geoenvironmental Engineering Division, ASCE.

Fenton, G. A. and Vanmarcke, E. H. (1991). Spatial variation in liquefaction risk assessment. Proceedings of the geotechnical Engineering Congress, Boulder, Colorado, USA. Geotechnical Special Publications, No. 27, Vol.1, pp. 594-607.

Idriss I. M. 1990. response of soft sits during earthquakes. Proceedings of H. Bolton Seed Memorial Symposium, Vancouver, BC, Canada, Vol.2, pp. 273-289.

Ishihara, K. 1993. Liquefaction and flow failure during earthquakes. Geotechnique, 43 (3): 351-415.

Ishihara, K. and Yoshimine, M. 1992. Evaluation of settlements in sand deposits following liquefaction during earthquakes. Soils and Foundations, 32 (1): 178-188.

O'Rourke, T. D and Pease, J. W. 1992. Large ground deformations and their effects on lifeline facilities; 1989 Loma Prieta earthquake. Case studies of Liquefaction and Lifeline Performance during Past Earthquakes; Volume 2, United States case studies. Technical Report NCEER-92-0002, pp. 5-1 – 5-85

O'Rourke, T. D and Pease, J. W. 1997. Mapping liquefiable layer thickness for seismic hazard assessment. Journal of the Geotechnical and Geoenvironmental Engineering Division, ASCE, 123 GT(1): 46-56.

Palisade Corporation. 1996. @Risk: Risk analysis and simulation add-in for Microsoft Excel or Lotus 1-2-3. Palisade Corporation, NY, USA.

Popescu, R., Prevost, J. H., and Deodatis, G. 1998. Characteristic percentile of soil strength for dynamic analysis. Proc. of the 1998 Conf. on Geotechnical Earthquake Eng. and Soil Dynamics III, Part 2 (of 2), Seattle, WA, USA, pp. 1461-1471.

Robertson, P. K. 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, 27 (1): 151-158.

Robertson, P. K. and Wride, C. E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal, 35 (3): 442-459.

Rollins, K. M. and McHood, M. D. 1998. Comparison of computed and measured liquefaction-induced settlements in the Marina District, San Francisco. The Loma Prieta, California, earthquake of October 17, 1989; Liquefaction. U. S. Geological Survey Professional Paper 1551-B, pp. 223-239.

Seed, H. B. and Idriss, I. M. 1971. Simplified procedure for evaluating soil liquefaction potential. Journal of Soil Mechanics and Foundation Division, ASCE, 97 (SM9): 1249-1273

Seed, R. B., Dickenson, S. E., and Mok, Chin Man. 1994. Site effects on strong shaking and seismic risk: recent developments and their impact on seismic design codes and practice. Proceedings of the Structures Congress '94, Atlanta, Georgia, USA. Vol.1, pp. 573-578.

Tokimatsu, K. and Seed, H. B. 1987. Evaluation of settlements in sands due to earthquake shaking. Journal of the Geotechnical Engineering Division, ASCE, 113, GT(8): 861-878.

Vanmarcke, E. H. 1984. Random fields, analysis and synthesis. MIT Press, Cambridge, MA, USA.

Vanmarcke, E. 1977. Probabilistic modeling of soil profiles. Journal of the Geotechnical Engineering Division, ASCE, 103 GT(11): 1227-1245.

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