NON-LINEAR PROBABILISTIC EVALUATION OF THE NUMBER OF EQUIVALENT UNIFORM CYCLES FOR LIQUEFACTION ANALYSES

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SUMMARY

Predictions of initial liquefaction for magnitude 5.25 and 7.5 events made using a deterministic model and current recommendations for uniform cyclic testing are compared to predictions made using a probabilistic model. Both deterministic and probabilistic analyses use the same pore pressure generation model. Results show that the two models agree well with respect to the maximum source distance within which liquefaction is expected, and that conventional factors of safety used with current recommendations for uniform cycle testing may be overly conservative for large magnitude events.

INTRODUCTION

While earthquake shear stress time histories actually consist of a large number of non-uniform load cycles, laboratory tests to evaluate liquefaction potential commonly are based upon a relatively small number of uniform load cycles. Recommendations for the number and magniude of uniform load cycles to use in laboratory evaluation of liquefaction potential as a function of earthquake magnitude and distance have been made by a number of investigators using the concept of linear accumulation of pore pressure (1, 2, 3). The development of excess pore pressure during cyclic loading is known to be a highly non-linear phenomenon, wherein the magnitude of pore pressure increase during any load cycle depends not only on the magnitude of the cyclic load but also on the excess pore pressure at the start of the load cycle. In this paper, probabilistic predictions of pore pressure generation as a function of earthquake magnitude and distance made using a model that accounts for non-linear pore pressure generation and non-uniform loading are compared to deterministic predictions of pore pressure generation during uniform cyclic loading.

Deterministic pore pressure ratios are predicted using a modified version of Seed, Martin, and Lysmer's pore pressure generation model (4) developed by Chameau to account for the influence of cyclic stress ratio on pore pressure development (5,6) and current recommendations for uniform cyclic loading (3). Probabilistic predictions are made with a stochastic model developed by Chameau using his modified pore pressure generation model to account for non-uniform seismic loading. Predictions are made for a hypothetical site composed of Monterey #0 sand subjected to magnitude 5.25 and 7.5 earthquakes.

Comparison of results indicate good agreement with respect to the source distance within which liquefaction is expected. At high levels of reliability, a very non-linear trend with respect to factor of safety,

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probability of liquefaction, and earthquake magnitude is observed. For the larger magnitude event, relatively small factors of safety are required to achieve high reliability.

HYPOTHETICAL SITE CHARACTERISTICS

The site for which predictions of pore pressure development were made was assumed to consist of a deep deposit of Montery #0 sand at a relative density of 50%. The water table was established at the horizontal ground surface and pore pressure development was evaluated for a point 5.2 m beneath the ground surface. Site characteristics are presented in Figure 1.

Seismic loading parameters for this hypothetical site were determined for magnitude 5.25 and 7.5 earthquakes using attentuation relationships developed by Echezuria (7). The loading parameters for the uniform cyclic loading model and the non-uniform loading model are the peak cyclic shear stress (PSS) and the root mean square of the shear stress time history (RMSS) respectively. PSS can be related to the peak ground acceleration (PGA), while the RMSS can be related to the root mean square of the acceleration time history (RMSA) based upon the total vertical stress, σ_o, and a flexibility factor, r_d.

$$PSS = r_d \; \sigma_o \; (PGA/g) \quad , \qquad (1a)$$

$$RMSS = r_d \; \sigma_o \; (RMSA/g) \quad , \qquad (1b)$$

where g is the acceleration of gravity and r_d is given by Seed and Idriss (8) for depths less than 20 m as

$$r_d = 1 - 0.01 \; d \qquad (2)$$

where d = the depth in meters.

Echezuria developed attenuation relationships for PGA and RMSA using the same data set of 83 strong motion records obtained within 110 Km. of the source from 18 different earthquakes of magnitude 5.0 or greater. Figure 2 presents the attenuation curves used in this analysis, produced by these relationships for magnitudes 5.25 and 7.5 earthquakes over the distance range pertinent to this study.

Properties of Montery #0 sand were determined based upon the results of uniform cycle laboratory tests performed at Stanford University. The cyclic strength and pore pressure generation curves developed from these test results are shown in Figures 3 and 4.

DETERMINISTIC UNIFORM LOADING MODEL

Deterministic pore pressure ratios due to uniform cyclic loading are predicted using a pore pressure generation model developed by Chameau (5), who modified the model developed by Seed, Martin, and Lysmer (4) to account for the influence of cyclic stress ratio on pore pressure generation. Chameau proposed an equation of the form

$$R = (1 - 2/\pi \; \arcsin \; (1 - \gamma_N)^{1/2\alpha})^{\beta} \qquad (3)$$

where R is the excess pore pressure ratio (excess pore pressure divided by initial effective stress, $\Delta U/\sigma_o'$), γ_N is the normalized number of cycles (number of cycles divided by the number of uniform cycles to liquefaction, N/N_L), and α and β are stress ratio dependent shape parameters.

The amplitude of the equivalent uniform cyclic shear stress is commonly expressed as a fraction of the PSS of the time history. Seed et al. (9) recommend a peak shear stress reduction factor of 0.65 for use in uniform cycle laboratory testing, with 2-3 cycles of loading recommended for M 5.25 earthquakes and 15 cycles of loading for M 7.5 earthquakes. Figures 5a and 6a show the pore pressure ratios predicted deterministically from equation 3 using the PSS values in Figure 2 and the soil properties shown in Figures 3 and 4. An important feature of these figures is the maximum distance at which liquefaction is predicted, equal to 2.5 km for the magnitude 5.25 earthquake and 31.2 km for the M 7.5 event.

Also plotted on Figures 5a and 6a is the factor of safety on the stress ratio required to induce liquefaction, FS_{SR}, defined as

$$FS_{SR} = \frac{0.65\ PSS}{SRL} \qquad (4)$$

where SRL is the stress ratio required to induce liquefaction in the recommended number of uniform cycles of loading (2-3 cycles for M 5.25 and 15 cycles for M 7.5).

PROBABILISTIC NON-UNIFORM LOADING MODEL

By assuming random arrivals of shear stress load cycles and a distribution shape for the magnitudes of the load cycles, Chameau created a stochastic model for non-uniform cyclic loading using his modified pore pressure generation model (5,6). This stochastic model predicts the probability of achieving any specified pore pressure ratio as a function of the RMSS, the number of positive zero crossings (load cycles) of the shear stress time history, and the distribution of the peaks of the time history. For this work the pore pressure ratio was set equal to 1.0 (initial liquefaction) and the peaks of the shear stress time history were assumed to correspond to a Rayleigh distribution. The Rayleigh distribution has been shown to be a reasonable one for describing the peaks of earthquake acceleration time histories (10,11,12).

Pore pressure generation was predicted using the RMSS attenuation relationship in Figure 1. The model also requires the number of positive zero crossings of the shear stress time history as input. Historgrams developed by Echezuria (7) for earthquakes with $M<6.25$ and $M>6.25$ were used in the analysis to describe the number of positive zero crossings for the M 5.25 and M 7.5 events, respectively. Figures 5b and 6b present the results of the non-uniform loading model, showing the probability of liquefaction versus distance for both events. Of particular interest in this figure are the distances at which the probability of initial liquefaction equals 0.50, 0.05 and 0.01. For the M 5.25 event, the probability of liquefaction equals 0.50 at 5.4 Km, 0.05 at 8.0 km, and it falls to 0.01 at 8.9 km. For the M 7.5, the probability of liquefaction equals 0.50 at 33.3 km, 0.05 at 38.2 km and 0.01 at 41.9 km. It is interesting to note that whereas the probability of liquefaction for the larger event is approximately equal to 1.0 within 25 km of the source, the probability of liquefaction for the smaller event never exceeds 0.90, even immediately adjacent to the source.

COMPARISON OF RESULTS

Table 1 compares the factor of safety from the deterministic analysis to the probability of liquefaction from the probabilistic analysis. The two models give consistent results with respect to the distance range within which liquefaction is expected. The probability of liquefaction at the maximum distance to liquefaction is greater than 0.5 in both cases, and the factor of safety is close to 1.0 when the probability of liquefaction equals 0.5 (indicating liquefaction is expected). When the factors of safety at high levels of reliability (low probability of liquefaction) for the two cases are compared, a very non-linear trend is observed. For the larger magnitude event with a relatively large number of equivalent loading cycles, a much smaller factor of safety is required to achieve the same reliability then for the smaller event. To achieve a reliability of 0.95, a factor of safety of 1.2 is required for the magnitude 7.5 event, while a factor of safety of 1.8 is required for the M 5.25 event. For a reliability level of 0.99, the M 7.5 event requires a factor of safety of 1.3, while the M 5.25 event requires a factor of safety of 2.0.

In Table 2, combinations of PSS reduction factor and number of uniform load cycles required to induce liquefaction according to the deterministic model at the distances at which the probabilistic model predicts a probability of liquefaction of 0.05 and 0.01 are presented. A laboratory specimen which did not experience initial liquefaction when subjected to one of these combinations of stress ratio and uniform cycles of loading would indicate at least the corresponding level of reliability, 0.95 or 0.99, for the design event. Note that a PSS reduction factor of 0.8, a magnitude 7.5 event, and a 0.05 reliability level, for which 14 uniform to liquefaction cycles are required, corresponds to a factor of safety of 1.2 based upon current recommendations for uniform cycle testing. Despite this low factor of safety, laboratory testing with a reduction factor of 0.65 yields no information on reliability, since a shear stress ratio of 0.65 PSS may be below the stress ratio required to induce liquefaction in less than 200 uniform cycles at large distances. The stress ratio required to induced liquefaction in 200 uniform cycles is the threshold below which the cyclic strength curve was not defined in the model.

SUMMARY AND CONCLUSIONS

Predictions of initial liquefaction have been made for a hypothetical site for M 5.25 and 7.5 events using a deterministic uniform loading model and a probabilistic model to account for non-uniform cyclic loading. Both models use the same pore pressure generation model to describe excess pore pressure development. Good agreement is observed with respect to the source distance within which initial liquefaction is expected between deterministic predictions made using current recommendations for uniform cyclic loading and the results of the probabilistic model.

Comparison of results at high reliability levels indicates a very non-linear relationship between reliability and factor of safety. For the larger magnitude event a relatively small factor of safety is required to achieve significant reliability levels. For the case presented herein, a factor of safety of less than 1.5 is required using current recommendations for uniform cycle testing to achieve a reliability of 0.99 for the M 7.5 event, while a factor of safety of 2.0 is required to achieve the same reliability for the M 5.25 event. This suggests that current recommendations for uniform cycle testing may be over-conservative when used with conventional factors of safety for large magnitude events.

ACKNOWLEDGEMENT

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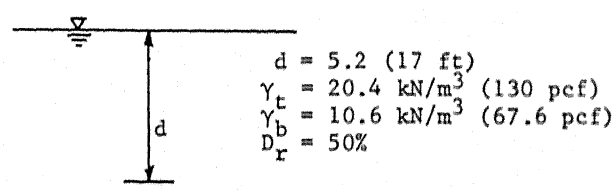
	FS_{SR}				
P_L	.99	.95	.50	.05	.01
M					
7.5	.800	.873	1.06	1.20	1.31
5.25	----	.873	1.40	1.83	1.98

TABLE 1 Factor of Safety Versus Probability of Initial Liquefaction

	N_{eq}			
	M = 5.25		M = 7.5	
RF	P_L = 0.05	P_L = 0.01	P_L = 0.05	P_L = 0.01
1.0	6	8-9	5-6	7-8
.9	9	13	8-9	12
.8	15	21	14	20
.7	30	65	28	>100
.65	53	--	--	---

TABLE 2 Number of Uniform Cycles versus PSS Reduction Factor Probability of Liquefaction



Monterey #0 Sand

Figure 1: Hypothetical Site

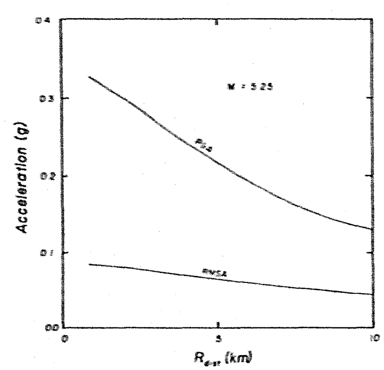


Figure 2a: M 5.25 Attenuation Curves

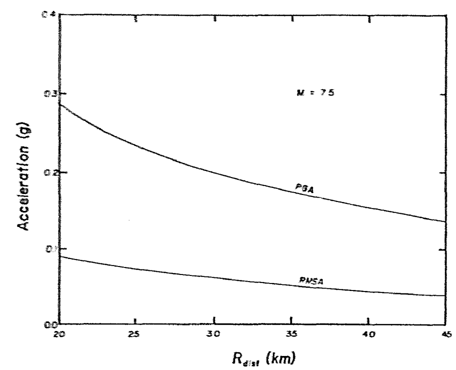


Figure 2b: M 7.5 Attenuation Curves

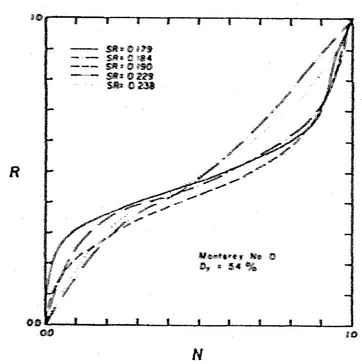


Figure 3: Pore Pressure Generation Curves

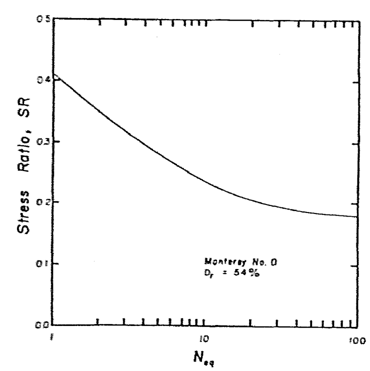


Figure 4: Cyclic Strength Curve

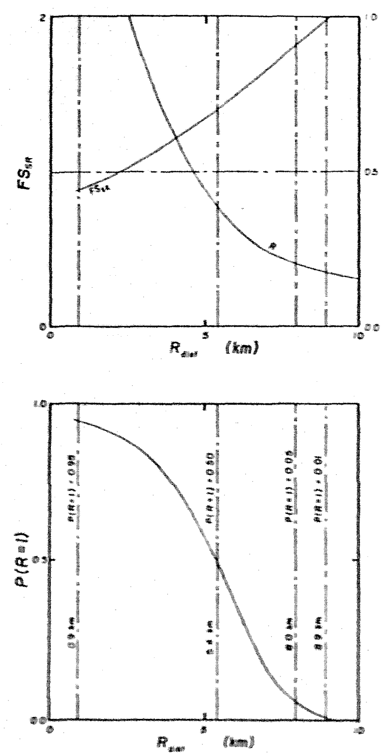


Figure 5: M 5.25 Liquefaction Predictions

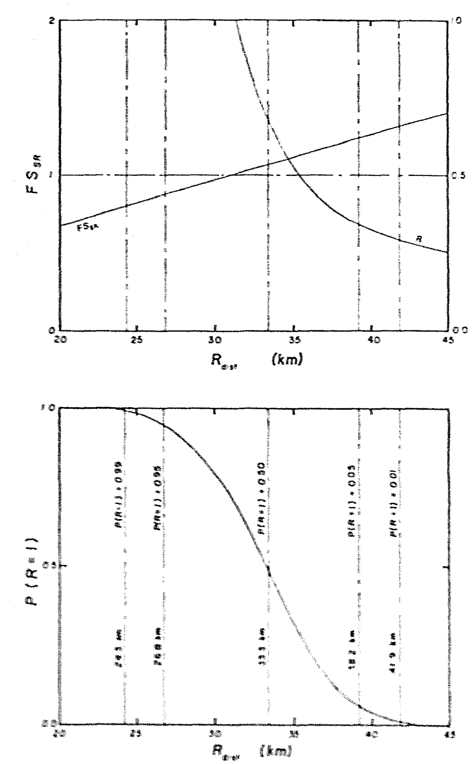


Figure 6: M 7.5 Liquefaction Predictions