PROBABILISTIC EVALUATION OF LIQUEFACTION WITH AN APPLICATION TO A SITE NEAR A SUBDUCTION ZONE

by

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SYNOPSIS

The probability of liquefaction occurrence during the life of a facility is calculated based on the cyclic strength of the subsurface saturated granular soils, the seismicity of the region and the two independent characteristics of earthquake shaking that affect the occurrence of liquefaction: (1) the level of the strong shaking, and (2) the duration of shaking. The method is applied to a site on the southern coast of Java, which is in a region of active subduction and with a history of large earthquakes.

INTRODUCTION

To determine the risk of liquefaction, it is important to know not only if liquefaction is possible, but also the probability of its occurrence during the life of a facility. The determination of the probability of liquefaction can be used to determine the cost-benefit of utilizing the site or improving the subsurface soil conditions. A method is presented to compute the probability of liquefaction at a site based on the seismicity of the region, the characteristics of ground shaking as a function of magnitude and distance, and the properties and conditions of the subsurface soils. The method consists of: (1) determining cyclic strength curves for the saturated granular soils, (2) establishing a correlation between earthquake magnitude and number of equivalent cycles of shaking, (3) developing a relationship between accelerations to cause liquefaction and cyclic strength, and (4) determining the probabilities of exceeding the accelerations that cause liquefaction at the site for each magnitude range in each zone of seismicity, and combining these probabilities to produce the overall probability of liquefaction. As indicated in the above procedure, the two basic ground motion parameters that influence liquefaction, levels of shaking and duration, are incorporated into the probabilistic model.

To illustrate the method, the probability of liquefaction is computed for a site on the southern coast of Java in a region of active subduction with a record of large magnitude earthquakes. The seismic input to the probability analysis required: (1) the delineation of the seismic boundaries of the region based on existing seismic and geologic data; (2) the estimation of earthquake recurrence rates, and (3) the determination of the attenuation of ground motion for earthquakes in each seismic zone. The soil data necessary for the

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study was obtained from laboratory testing of undisturbed soil samples.

METHOD

Parameters Influencing Liquefaction: From the standpoint of earthquake ground motion, the occurrence of liquefaction depends basically on two parameters: (1) the level of shaking, and (2) the duration of shaking. A high level of shaking or a long duration alone does not necessarily mean that liquefaction will occur.

The significant soil properties that influence the potential for liquefaction are soil type, void ratio, degree of saturation, and initial confining pressure (Seed and Idriss, 1971). Soils particularly susceptible to liquefaction are saturated granular materials with relatively high void ratios.

Considering both the characteristics of the earthquake ground motion and the properties of the soil, liquefaction is likely to occur when the induced earthquake stresses in the soils acting for a given period of time exceed the available cyclic strength of the soil.

Correlation of Laboratory Measurements with Ground Motion Parameters: A current procedure to define the liquefaction strength of soils is from the results of cyclic triaxial testing. In such tests, a cylindrical sample is confined under a representative overburden pressure, and the ends of the sample are subjected to cyclic loads until the sample fails. The laboratory liquefaction potential of the soil is defined in terms of two parameters: (1) the ratio of the maximum cyclic shear stress to the effective confining pressure of the sample (stress ratio), and (2) the number of cycles to predetermined failure criteria. The results of a series of these tests on many soil samples are plotted as points on a graph relating these two parameters (Fig. 1). The line labeled "Laboratory Strength" represents the liquefaction strength curve. The shape of the curve is typical of fatigue failures for many materials.

In general the laboratory strength of the soil sample is greater than the field strength due to the limitations of laboratory techniques. Typical estimated corrections (c_r) indicated that the field strength is between approximately 0.6 and 0.8 of the laboratory strength. Figure 1 shows the "Field Strength" as approximately 0.7 of the laboratory strength.

Given the field strength curve, the graph must now be expressed in terms of ground motion parameters that can be used to compute probabilities of liquefaction. According to the simplified procedure of Seed and Idriss (1971), a simplified relationship exists between earthquake magnitude and number of cycles. The greater number of cycles indicate longer durations of strong shaking which in turn indicate greater magnitude. The correlation of number of cycles with magnitude indicated by the horizontal scales shown in Figure 3 has been extrapolated to magnitude 5, which was considered the smallest earthquake that can cause liquefaction at the site. As seen in Figure 3, a magnitude 8 earthquake is considered equivalent to 30 cycles.

The stress ratio is correlated with the peak ground acceleration by computing the variation of the dynamic shear stresses with depth for various maximum surface accelerations (Seed and Idriss, 1971). For the example discussed here the simplified Seed and Idriss (1971) procedure was used. This simplified procedure for estimating the variation of shear stresses with depth consists of computing the shear stress necessary to accelerate a rigid soil column to a prescribed peak acceleration and then multiplying the results by simple reduction factors which account for the deformability of the soil and the lack of uniformity of earthquake induced stresses. As shown in Figure 2, the ratios of the average shear stress to overburden pressure (solid lines) and the field strength stress ratio (dashed lines) were plotted with depth to illustrate the potential zones of liquefaction. For example, the zone of liquefaction is below about 15 feet (Fig. 2) for a magnitude 8 earthquake (30 cycles) producing a peak ground acceleration of 0.2g. For this size of earthquake, the minimum induced stress necessary to initiate liquefaction occurs at 30 feet and corresponds to a peak acceleration of about 0.17g. The correlation of magnitude and minimum peak accelerations for which liquefaction will occur is shown in Figure 3.

Calculation of Probabilities: With the soil strengths correlated in terms of the ground motion parameters in Figure 3, the probabilities of liquefaction at the site can be computed. The probability that liquefaction will occur at least once in some time period, T, is computed with the following formula:

$$\text{Probability of Liquefaction} = 1 - \prod_{j=1}^{n} \prod_{i=1}^{m_j} \sum_{k=0}^{\infty} (1-p_{ij})^k P_{ij}(k) \qquad (1)$$

This equation was derived from the binomial distribution formula for zero successes in k repeated Bernoulli trials and the law of total probability (Benjamin and Cornell, 1970). The example below illustrates the details of the calculation.

The symbol p_{ij} is the probability that one earthquake in some small magnitude range (i) occurring in some seismic zone (j) produces a peak ground acceleration at the site which would cause liquefaction. The basis for computing p_{ij} is to assume that earthquakes can occur anywhere within the seismic zones; its value is a function of the attenuation of peak acceleration with magnitude and distance, the geometry of the seismic zones, and their location with respect to the site. The occurrence of any number of earthquakes in time T for a particular magnitude range and seismic zone is accounted for by the appropriate temporal probabilistic distribution, $P_{ij}(k)$. The parameters of this probabilistic distribution can be computed from the instrumental record of seismicity. The summation process is carried through a sufficient number of terms to achieve the desired precision.

EXAMPLE

To illustrate the method, the probability of liquefaction in 25 years is computed for a site on the south coast of Java. An example calculation is given for only one seismic zone in the region; however, the procedure for computing the probabilities for each zone and combining them to produce the overall probability of liquefaction is explained.

The first step is to define the seismic zone in the site region based on its seismicity and geology. The seismicity of this region (Fig. 4) is due to the subduction of the Indian Plate beneath the Eurasian Plate. In order to define the boundary of the subducting plate, the seismicity within the rectangular area of Figure 4 was projected on a vertical plane passing through line AA′. The resulting hypocentral profile (Fig. 5) was the basis for constructing the four seismic zones shown as cross-hatched rectangles. The zonation consisted of three zones associated with the Benioff zone and a shallow zone which accounted for the seismicity on the island of Java and the Java Sea. The shallow zone in the Java Trench is used in the example calculation.

A recurrence curve was established for each zone relating the number of earthquakes per year per square km in each one-half unit of magnitude. The recurrence curve was assumed to be linear up to the upper bound magnitude which was established for each zone. The recurrence curve was used to compute the mean rate of occurrence, v, of the Poisson temporal distribution function denoted as $P_{ij}(k)$ in equation (1) and Table 1. Other temporal distributions, such as the Weibull process, could also be used, but for purposes of illustrating the method the Poisson process was assumed.

The available information on the attenuation of ground motion in the region indicated that the use of an updated version of Housner′s (1970) relation would be appropriate for the shallow seismicity and that Donovan′s (1973) relation would be appropriate for the seismicity at depths greater than 35 km. The updated Housner′s relationship correlating the areas within which different levels of acceleration are felt for earthquakes in various magnitude ranges is:

	Area (1000 km^2)			
Magnitude	0.1g	0.2g	0.3g	0.4g
5.0-5.4	0.5	0.2	0.03	-
5.5-5.9	1.3	0.6	0.2	0.03
6.0-6.4	3.3	1.4	0.6	0.2
6.5-6.9	7.3	3.0	1.0	0.4
7.0-7.4	15.8	7.8	2.0	0.8
7.5-7.9	40.0	19.4	7.3	1.8
8.0-8.4	66.0	35.7	20.7	4.5

Donovan′s (1973) attenuation formula relates the mean peak ground acceleration to earthquake magnitude (1973) and hypocentral distance. These attenuation relationships were used to compute the probabilities p_{ij} in equation (1) for each magnitude range and each seismic zone. For example, if Housner′s updated attenuation relationship is used, p_{ij} is computed as the ratio of the vulnerable area within the seismic zone to the total area of the seismic zone. The vulnerable area is that area such that an earthquake of a given size occurring anywhere within its boundary will cause liquefaction at the site. Since Donovan gives the distribution of peak acceleration values about the mean (log-normal), p_{ij} can be computed from his attenuation formula by integrating over the entire zone according to the law of total probability (Benjamin and Cornell, 1970).

As indicated by the second term in equation 1, the probability that liquefacion will not occur is the first computed for each zone. The computation of the probability that liquefaction will not occur at the site in 25 years due to earthquakes in the shallow seismic zone in the Java Trench (Fig. 5) is illustrated in Table 1. According to Housner's attenuation relation, only earthquakes above magnitude 7 can cause liquefaction at the site because of the distance between the closest boundary of the zone and the site. The peak accelerations at the site necessary to cause liquefaction were obtained from Figure 3 for each magnitude range and are shown in column 3 of Table 1. The average number of earthquakes per year for each magnitude range (column 2 of Table 1) was computed from the recurrence curve and used to compute $P_{i1}(k)$ (Table 1). The values in the last column of the table are the probabilities that liquefaction will not occur for each magnitude range. The product of these numbers (.967) is the probability that liquefaction will not occur for all sizes of earthquakes in this zone. Similarly, the probabilities that liquefaction will not occur due to the seismicity in the other zones can be computed. The product of these probabilities subtracted from unity gives the probability that liquefaction will occur at least once at the site in 25 years (equation 1).

BIBLIOGRAPHY

Benjamin, J. R., and Cornell, C. A. (1970), Probability, Statistics, and Decision for Civil Engineers. McGraw-Hill, p. 58, 242.

Donovan, N. C. (1973), "A Statistical Evaluation of Strong Motion Data Including the February 9, 1971, San Fernando Earthquake," Proc. Fifth World Conf. Earthquake Engr., Rome, Italy, p. 1252-1261.

Housner, G. W. (1970), "Strong Ground Motion," Earthquake Engineering, R. L. Wiegel (ed.), p. 80.

Seed, H. B., and Idriss, I. M. (1971), "Simplified Procedure for Evaluating Soil Liquefaction Potential," J. Soil Mech. Found. Div. ASCE, SM 9, p. 1249-1273.

MAGNITUDE RANGE	NO OF EARTHQUAKES/Yr ν	PEAK ACCELERATION (FIGURE 3)	φ_{i1} (Eqn. 1)	$\sum_{k=0}^{\infty}(1-\varphi_{i1})^k P_{i1}(k)$ (Eqn. 1)*
7.0 - 7.4	.04	.20g	.00272	.997
7.5 - 7.9	.02	.18g	.0178	.991
8.0 - 8.4	.01	.18g	.0878	.978

$$P\,(\text{No liquefaction}) = \prod_{i=1}^{3} \sum_{k=0}^{\infty} (1-\varphi_{i1})^k \; P_{i1}(k) = .967$$

* $P_{i1}(k)$ is Poisson Distribution with mean = νT

$$P_{ij}(k) = \frac{(\nu T)^k}{k!} e^{-\nu T}$$

TABLE 1. EXAMPLE CALCULATION OF PROBABILITY OF LIQUEFACTION NOT OCCURRING IN T = 25 YEARS.

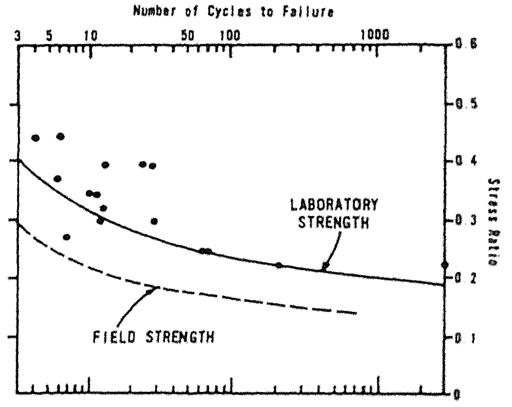

FIGURE 1. LIQUEFACTION STRENGTH CURVE

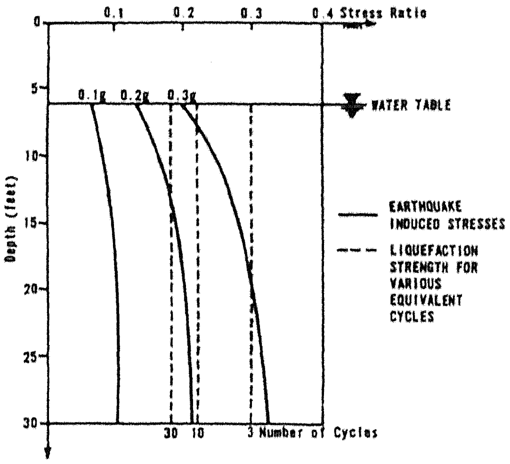

FIGURE 2. LIQUEFACTION POTENTIAL AT SITE

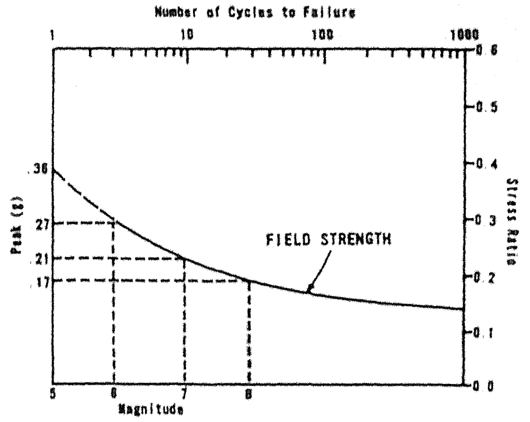

FIGURE 3 CORRELATION OF LIQUEFACTION STRENGTH AND GROUND MOTION PARAMETERS

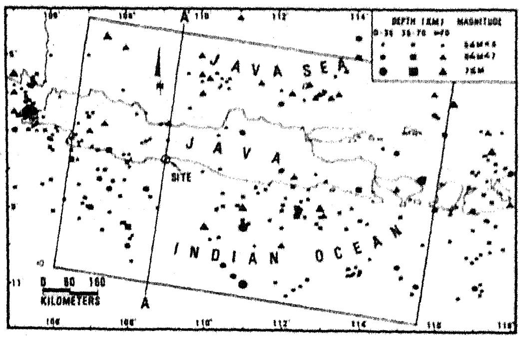

FIGURE 4. EPICENTER MAP (1911-1974)

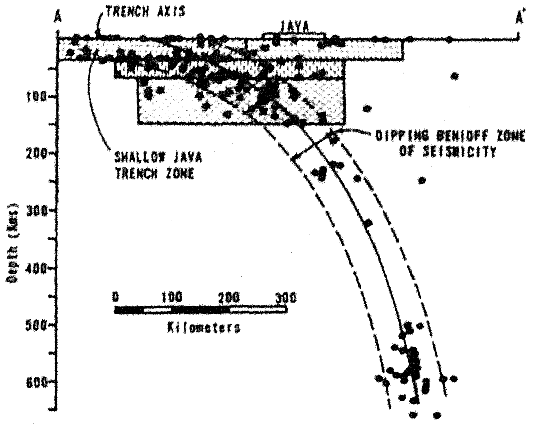

FIGURE 5. HYPOCENTRAL PROFILE AND SEISMIC ZONES