PROBABILISTIC SEISMIC HAZARD
ANALYSIS FOR PORE PRESSURE
BUILD-UP IN SANDS

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SUMMARY

A Seismic Hazard Analysis for earthquake-induced pore pressures in sands is proposed. The method employs a model for probabilistic prediction of excess pore pressures given the earthquake magnitude and its distance from a site. The model, when incorporated in conventional Seismic Hazard Analysis procedures using the computer, can provide estimates of annual probabilities of excess pore pressures exceeding specified values.

This paper presents both the model for probabilistically predicting excess pore pressures and the procedure for Seismic Hazard Analysis for pore pressures. In addition, discussions are included on the application of the Seismic Hazard Analysis in an Integrated Seismic Risk Analysis which provides estimates of overall risk associated with excess pore pressures generated in loose sands during earthquakes.

INTRODUCTION

Earthquake-induced liquefaction of sands has received extensive attention by researchers and engineers for many years. Analytical procedures have been developed for calculating the factor of safety against liquefaction of sand deposits. While a computed factor of safety greater than 1.0 may indicate safety against liquefaction failure of a particular sand deposit, the possibility of significant excess pore water pressure generated during the postulated earthquake cannot be disregarded. Such increase in excess pore pressures can reduce the effective stresses in the sand to levels consequential to the dynamic and post-earthquake static performance of the deposit. Thus, in earthquake engineering practice, it is desirable to ensure that the excess pore pressures generated at a site are below a limiting level. This can be accomplished by ensuring that the value of the computed factor of safety against liquefaction is greater than 1.0 by an appropriate margin.

The calculation of the factor of safety against liquefaction and the determination of the safety margin required in order to limit the excess pore pressures below a value selected in design involve many sources of uncertainty including: the seismicity of the region in which the site is located, the site condition and soil parameters, and the analytical procedures used for calculating the factor of safety and for predicting the level of excess pore pressures generated. To account for most of these uncertainties, a probabilistic Seismic Hazard Analysis for pore pressures is developed which employs an empirical method of excess pore

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pressure prediction in terms of earthquake magnitude and hypocentral distance with conventional probabilistic Seismic Hazard Analysis procedures utilizing the computer. The results of the proposed methodology are expressed in terms of annual probabilities of excess pore pressure exceeding limiting values much in the same manner as is typically done for ground acceleration.

A practical application of the proposed procedure for Seismic Hazard Analysis for pore pressure is that it can be combined with the results of Seismic Performance Analysis in which probabilistic predictions of the performance of a facility considering various levels of excess pore pressures building up in the foundation sands, is made. Such an integration of the results of the seismic hazard and seismic performance analysis can provide estimates of the overall risk of damages to or failure of the facility founded on a sand deposit.

This paper discusses both the procedure for pore pressure prediction and the probabilistic seismic hazard methodology which employes this pore pressure model. In addition, discussion are presented on the applications and benefits of the proposed methodology in engineering practice. An example application of the procedure is included.

PORE PRESSURE PREDICTION MODEL

For a probabilistic evaluation of liquefaction potential of a sand deposit Yegian (1981) proposed an empirical method based on an expanded list of case histories of liquefaction and non-liquefaction of sand deposits.

The parameter Liquefaction Potential Index (LPI) was used as defined in Eq. 1.

$$LPI = \frac{e^{0.2M}\ (R+25)^{-0.4}}{0.46\ \ N_c^{\ 0.4}} \cdot \frac{\sigma_v}{\bar{\sigma}_v} \tag{1}$$

Where M is the earthquake magnitude in the Richter scale, R is the hypocentral distance in kilometers, σ_v is the total vertical stress at the point of interest within a sand deposit, $\bar{\sigma}_v$ is the effective vertical stress at that point and N_c is the standard penetration test value (SPT), corrected for the overburden pressure as suggested by Seed (1976)

$$N_c = N(1-1.25 \log \bar{\sigma}_v\ (TSF)) \tag{2}$$

Equation 1 when used with average values of soil parameters can indicate deterministically if liquefaction is likely to occur (LPI > 1.0) or not (LPI < 1.0).

The evaluation of LPI for a particular sand deposit involves various sources of uncertainty. The expression for the coefficient of variation of LPI, V_{LPI}, from Ref. 1 is

$$V^2_{LPI} = 0.035 + 0.16V_N + [\,1 + (\frac{\sigma_v}{\bar{\sigma}_v})^2]V_\gamma + (\frac{dw\,\gamma_w}{\bar{\sigma}_v})^2\ V_{dw} \tag{3}$$

where V_N, V_Y and V_{dw} are the coefficients of variation of the field standard penetration test value, the unit weight of the soil and the depth of the ground water table respectively. Typical values of V_{LPI} range between 0.2 to 0.50.

If for a particular sand deposit the computed average LPI is less than 1.0, although it indicates that liquefaction is not expected to occur, significant amount of excess pore water pressures may still be generated within the deposit. The amount of excess pore pressure, typically measured in terms of the pore pressure response parameter r_u, depends on the margin of safety available against liquefaction. The smaller (less than 1.0) the value of LPI, the smaller is the excess pore pressure, Δu.

Yegian (1980) proposed an empirical procedure for predicting earthquake-induced excess pore pressures in sands. The methodology employs the parameter LPI to define the threshold event causing 100% pore pressure response. This defines an anchor point on a curve relating pore pressure reponse to earthquake intensity expressed in terms of magnitude and distance from the site. The intermediate relationship between zero response to 100% is established using the trends observed from laboratory based curves relating pore pressure response to normalized number of cycles. The details of the derivations of the model are presented in Ref. 2. The final relationship established between LPI and r_u is expressed in Eq. 4

$$r_u = \frac{\Delta u}{\bar{\sigma}_v} = \frac{2}{\pi} \text{arc sin } (\text{LPI})^{\frac{1}{2\alpha\beta}} \text{ ; LPI} \leqslant 1.0 \qquad (4)$$

where α and β are curve fitting parameters obtained from laboratory test data as described in Ref. 2. Typical values of α range between 0.5 and 1.0 and for β between 0.1 and 0.25.

Thus, using Eqs. 1 and 4 the pore pressure response parameter r_u can be related to earthquake magnitude and distance and to the site parameters. The attractiveness of this procedure for predicting seismically-induced pore pressures is that it benefits from a methodology for predicting liquefaction, based on a large number of field observations instead of solely relying on laboratory test data for the particular sand under investigation. In addition, relating the pore pressure respone parameter, r_u to earthquake magnitude and distance, inherently considers the effect of duration and number of cycles, since both are functions of the size of the earthquake. Thus, the pore pressure prediction model described herein lends itself conveniently for direct adoption in conventional Seismic Hazard Analysis procedure originally proposed by Cornell (1968) as will be described subsequently. Chameau and Clough (1983) proposed a Seismic Hazard Analysis procedure for pore pressures which combines the results of hazard analysis for acceleration with the probability of pore pressure build-up given that the ground acceleration exceeds different levels. The pore pressure prediction model developed herein through the use of magnitude and hypocentral distance can be directly incorporated into conventional Seismic Hazard Analysis procedures, thus avoiding the problems associated with the two-step procedure described by Chameau and Clough (1983).

SEISMIC HAZARD ANALYSIS FOR PORE PRESSURES

Cornell (1968) proposed a methodology for probabilistic evaluation of seismic hazard at a site. The results from a Seismic Hazard Analysis typically consist of probabilities that a given seismic parameter exceeds specified values. Very often this seismic parameter used is peak ground acceleration. The calculations involved in a Seismic Hazard Analysis are usually performed utilizing computers. Among the input information for such an analysis is an attenuation law which relates the seismic parameter to earthquake magnitude and distance. If a Seismic Hazard Analysis for acceleration is to be made, an acceleration attenuation law would be required.

Yegian (1981) described liquefaction risk analysis which utilizes Eq. 1 as an attentuation law in the Seismic Hazard Analysis. The probability of liquefaction then would be given by

$$P[LIQ] = P[LPI > 1.0] \qquad (5)$$

Thus, a Seismic Hazad Analysis which employes Eq.1 as an attenuation law and in which the value of LPI is assigned to be equal to 1.0 will yield the probability of liquefaction or the annual number of seismic events which would cause liquefaction.

In a similar way the probability of pore pressure response parameter r_u exceeding a specified value say x% can be calculated by assigning the value of LPI obtained from Eq. 3 using r_u= x%. For example, to calculate the annual probability of the pore pressure parameter exceeding 50%, in the computer analysis, the value of LPI to be used should be equal to 0.91 and the associated coefficient of variation is given by Eq. 3. Table 1 shows the format for a discrete functional presentation of the results obtained from the proposed Seismic Hazard Analysis for pore pressures. The use of this format facilitates the integration of the Seismic Hazard and Seismic Performance Analyses results to obtain an estimate of the overall risk.

APPLICATION IN INTEGRATED SEISMIC RISK ANALYSIS

The evaluation of the overall seismic risk of damages to or failure of a facility founded on a saturated loose sand deposit will require in addition to the results of a Seismic Hazard Analysis for pore pressures the results of a probabilistic Seismic Performance Analysis in which the probability of damages or failure of the facility is estimated considering that in the free field (level ground) condition the pore pressure response parameter, r_u, has a specified value. The estimation of these conditional probabilities involves application of soil dynamics and probabilistic procedures which consider the uncertainties in the soil parameters and analysis methods employed. The results of a Seismic Performance Analysis provide probabilistic predictions of response in terms of damages or failure of the facility given that there are excess pore pressures in the free field adjacent to the facility. The details of the procedures for calculating these conditional probabilities of damages or failure using free field excess pore pressure is beyond the scope of

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this paper. These conditional probabilities can be expressed in t of a damage probability matrix as shown in Table 2. In this $P[D_i|r_{uj}]$ is the conditional probability of damage state D_i which i associated with the free field excess pore pressure given by r_{uj}.

The integration of the results of Seismic Hazard Analysis (Ta and Seismic Performance Analysis (Table 2) will yield the seismi Eq. 6 can be used to perform this integration in discrete functiona

$$\lambda(D_i) = \sum_{\text{all } j} P[D_i|r_{uj}] \cdot \lambda(r_{uj})$$

where $\lambda(D_i)$ is the annual number of seismic events causing damage D_i, $\lambda(r_{uj})$ is the annual number of seismic events which would cau excess pore pressures in the free field in the range of $P[D_i|r_{uj}]$ is the probability of damage state D_i conditional to the occurence of excess pore pressure build-up in the range of r_{uj}. If occurence of seismic events and of associated damages are assu follow a poisson arrival process, then the annual probability of at one event causing damage level to exceed D_i can be obtained from

$$P[D_i \text{ or greater}] = 1 - e^{-\lambda(D_i \text{ or greater})}$$

The proposed <u>Integrated Seismic Risk Analysis</u> for a facility f on loose saturated sands susceptible to developing excess pore pre during earthquakes provides estimates of risks in terms per comparison with risks associated with other natural or man-made c In addition, it can identify the importance and implications of v assumptions, hypothesis and criteria used in the seismic design or evaluation of the facility.

EXAMPLE APPLICATION OF SEISMIC HAZARD ANALYSIS FOR PORE PRESSURES

To illustrate the application of the proposed Seismic Hazard An for pore pressures, a hypothetical problem is selected and invest herein. Fig. 1 shows this example problem of an embankment founded layer of loose sand. It is assumed that the embankment is loca Boston, Mass., thus the seismic source models used by Tong, Schum Cornell and Whitman (1975) for the New England region would be used Seismic Hazard Analysis.

<u>Site Characteristics</u>

The expression for LPI given by Eq. 1 can be written as

$$LPI = K_1 e^{0.2M} \quad (R+25)^{-0.4}$$

where K_1 is a site parameter which describes the site condition from geotechnical engineering point of view, and is given by

$$K_1 = \frac{1}{0.46\ N_c^{0.4}} \cdot \frac{\sigma_v}{\bar{\sigma}_v} \qquad (9)$$

For the example problem, the site parameter K_1 for the free field condition at some distance away from the toe of the embankment is assumed to be equal to 1.0. It is further assumed that the values of α and β in Eq. 4, for the foundation sand, are 0.7 and 0.19 respectively.

Seismic Hazard Analysis for Pore Pressures

The seismic source areas shown in Fig. 2 and the relevant seismic parameters described in Ref. 5 were used in the computer program prepared by Cornell and Schumacker at M.I.T. To related earthquake magnitude and distance to the pore pressure response r_u, Eq. 8 with K_1=1.0 and Eq. 4 were used. The calculation of the annual probability of exceeding a specified value of r_u was made by specifying in the computer analysis the corresponding value of the LPI obtained from Eq. 4. For example, to calculate the annual probability of r_u exceeding 0.5, the value of the LPI read in was 0.91. Thus,

$$P[r_u > 0.5] = P[\mathrm{LPI} > 0.91] \qquad (10)$$

The Seismic Hazard Analysis was repeated for various values of LPI using a coefficient of variation of LPI = 0.35. Table 1 summarizes the results of these Seismic Hazard Analyses in discrete functional form. These results, together with the results of a Seismic Performance Analysis can be used to estimate the overall risk associated with the earthquake induced pore pressures in the foundation sands of the embankment.

Seismic Performance Analysis

The probabilistic evaluation of the seismic performance of the example embankment is beyond the scope of this paper. Basically, the task involves, for each specified level of excess pore pressure in the free field, the estimation of the pore pressure below the embankment and the associated seismic response of the embankment. Probability procedures would then be used together with criteria defining different damage states and failure to evaluate the conditional probabilities of damage to or failure of the embankment.

For the example problem, to permit the calculations of the overall seismic risk, these conditional probabilities were selected solely on a subjective basis and are shown in Table 2.

Integrated Seismic Risk Analysis

The calculation of the seismic risk of damage to or failure of the embankment involves the integration of the results shown in Tables 1 and 2 using Eq. 6. For example, the annual number of events causing failure would be obtained as follows:

$$\lambda(\text{Failure}) = (0.5\text{x}18.5+0.45\text{x}0.5+0.4\text{x}3+0.3\text{x}5+0.2\text{x}6+0.1\text{x}13)\text{x}10^{-4}$$
$$= 14.7 \text{ x } 10^{-4} \text{ events/year}$$

The probability of at least one event causing failure in 50 years is then given by

$$P[\text{Failure}] = 1-e^{-\lambda(\text{Failure})\text{x}50} = 1-e^{-(14.7\text{x}10^{-4})\text{x}50} = 0.07 = 7\%$$

Table 3 summarizes the results of these integrations. Such information can be useful in an engineering design decision process, in which trade-offs are made between costly designs for greater resistance of the facility and more economical designs associated with higher risks of economic and human losses.

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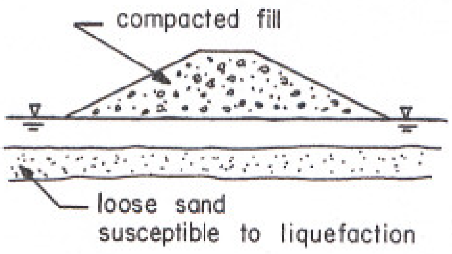

FIG. I Example Problem

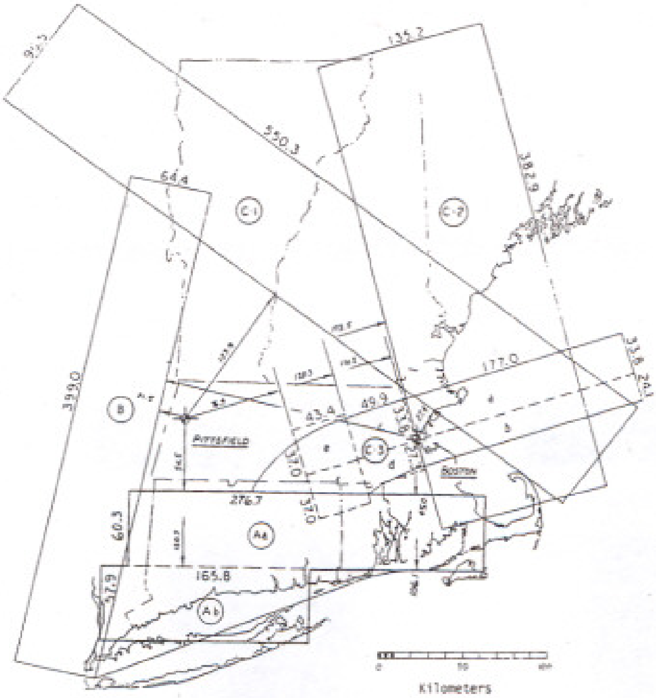

FIG. 2 Seismic Source Zones for the Example Problem

TABLE 1 SEISMIC HAZARD ANALYSIS

r_u = pore pressure parameter

	$r_u < .4$	$.4 \le r_u < .5$	$.5 \le r_u < .6$	$.6 \le r_u < .7$	$.7 \le r_u < .8$	$.8 \le r_u < .9$	$.9 \le r_u \le 1.0$
AVERAGE NUMBER OF ANNUAL EVENTS	$>20\times10^{-5}$	13×10^{-4}	6×10^{-4}	5×10^{-4}	3×10^{-4}	0.5×10^{-4}	18.5×10^{-4}

TABLE 2. DAMAGE PROBABILITY MATRIX $P[D_i \mid r_{uj}]$

DAMAGE STATE Di	$r_u < .4$	$.4 \le r_u < .5$	$.5 \le r_u < .6$	$.6 \le r_u < .7$	$.7 \le r_u < .8$	$.8 \le r_u < .9$	$.9 \le r_u \le 1.0$
NO OR MINOR	1.0	0.7	0.5	0.4	0.25	0.15	0.05
HEAVY	0	0.2	0.3	0.3	0.35	0.4	0.45
FAILURE	0	0.1	0.2	0.3	0.4	0.45	0.5

TABLE 3. INTEGRATED SEISMIC RISK

DAMAGE STATE Di	ANNUAL NUMBER OF EVENTS	PROBABILITY IN 50 YEARS
NO OR MINOR	$>20\times10^{-4}$	86 %
HEAVY	15.5×10^{-4}	7 %
FAILURE	14.7×10^{-4}	7 %

TABLES 1, 2 and 3