EMPIRICAL PROCEDURE FOR PORE PRESSURE PREDICTION IN SANDS

by

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ABSTRACT

In recent years, geotechnical earthquake engineers have accorded increasing importance to dynamic effective stress analysis and settlement calculations for structures founded on loose, saturated sands. This has prompted the development of pore pressure prediction models for saturated sands by various researchers.

The procedures currently used for the estimation of pore pressures in the field are based on the earthquake-induced shear stresses obtained from the application of the one-dimensional shear wave propagation theory, and on the laboratory pore pressure data on cyclically-loaded specimens of sands. Such procedures for pore pressure prediction not only involve many uncertainties, but also are complicated and expensive to apply.

This paper describes a simple, empirical procedure for pore pressure prediction in loose, saturated sands based on both field observation of liquefaction and basic laboratory behavior of loose, saturated sands. The procedure employs earthquake magnitude and hypocentral distance to describe the intensity of earthquake shaking at a site. The soil condition is expressed in terms of the standard penetration test value. Thus, for a given earthquake of magnitude M and hypocentral distance R, the model can predict the pore pressures with depth of sandy profiles which are described by their SPT-values with depth.

This new model developed for the prediction of pore pressures in loose, saturated sands is simple to apply and enables quick evaluation of pore pressures for preliminary studies.

The model also provides an opportunity to combine future field data and laboratory data on pore pressures in a simple, logical and consistent manner.

An example of the specific application of the model is provided in the paper.

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INTRODUCTION

Liquefaction is a failure phenomenon which occurs in loose, saturated sands. A liquefaction study in the laboratory is often associated with a study of the excess pore pressure of the sand. Liquefaction (or "initial liquefaction") is said to occur if the pore pressure response, r_u, is equal to 1. Equation 1 gives the pore pressure response,

$$r_u = \frac{\Delta u}{\bar{\sigma}_v} \tag{1}$$

in which Δu is the excess pore water pressure for level ground conditions. Thus, a pore pressure response of 100% ($r_u = 1$) indicates that the sand under study has liquefied. In engineering practice, liquefaction analysis using laboratory cyclic strength data involves the determination of whether or not for a given seismic event the pore pressure response is greater than 1. Thus, a computed factor of safety (defined by the ratio of cyclic strength to shear stress) against liquefaction greater than 1.0 may indicate that the sand is not likely to liquefy, but does not indicate the level of excess pore pressure that might still be generated during that particular event. Such increases in excess pore pressure below levels causing initial liquefaction may still be of such magnitude as to reduce the effective stresses in the soil to levels consequential to the dynamic response of the deposit and to the stability and settlement of a structure founded on the deposit.

Hence, in practice, liquefaction analysis should include the prediction of excess pore pressures, which then can be used in the study of the performance of the soil-structure system during and after a design seismic event.

In this paper, a simple method for the prediction of earthquake-induced pore pressures in sands is presented. The method can also provide a relationship between the computed factor of safety against liquefaction and pore pressure response for level ground conditions. The following sections briefly describe the prediction model and discuss its practical implications. Results of an example study of a typical deposit of loose sand are presented.

PREDICTION MODEL

The pore pressure prediction model combines an empirical method of liquefaction analysis to define a threshold event causing 100% pore pressure response with normalized laboratory soil behavior curves, to predict the excess pore pressure generated during events smaller than the event causing liquefaction.

Field Liquefaction Model

The Liquefaction Potential Index (LPI) proposed by Yegian and Whitman (1978) is employed to evaluate the liquefaction potential at a site. The definition of LPI is given as:

$$\text{LPI} = \frac{\text{Earthquake-induced shear stress}}{\text{Shear strength against liquefaction}} \tag{2}$$

Thus, if LPI > 1.0, liquefaction of the sand is expected to occur; and if LPI < 1.0, liquefaction is not expected to occur at the site. Note that LPI is actually the reciprocal of the conventional factor of safety against liquefaction as defined by the ratio of shear strength to shear stress,

$$\text{LPI} = \frac{1}{\text{Factor of Safety}} \tag{3}$$

Yegian and Whitman (1978) proposed an empirical liquefaction analysis based on the interpretation of field data in terms of earthquake magnitude, M, and hypocentral distance, R. The resulting LPI is expressed as:

$$\text{LPI} = \frac{e^{0.5M_H}}{(R+16)\,\bar{\sigma}_v\,\bar{S}_c} \tag{4}$$

in which M is the Richter-scale magnitude, H is the depth in feet of the point of interest, R is the hypocentral distance in miles, and $\bar{\sigma}_v$ is the vertical effective stress in psi at depth H. The parameter $\bar{S}_c$ is a strength parameter and is a function of the corrected standard penetration test values, N'. Yegian and Whitman proposed a plot relating $\bar{S}_c$ to N' based on empirical observations of liquefaction and no liquefaction. Thus, for a given sand deposit and a postulated seismic event characterized in terms of earthquake magnitude and hypocentral distance, it is possible to compute the LPI (or the factor of safety).

If the sand deposit considered for the study is not "safe" against liquefaction (LPI > 1.0), the pore pressure response is expected to be 100%. However, if the deposit is not likely to liquefy (LPI < 1.0), a further investigation is still needed to determine the excess pore pressure or the pore pressure response r_u. To evaluate r_u under these conditions, laboratory data are utilized as described in the following section.

Laboratory Soil Behavior

Data on laboratory strength against liquefaction is typically presented in the form of a plot of the ratio of cyclic shear stress causing liquefaction to the vertical effective stress versus the logarithm of the number of applied uniform cycles. Figure 1 presents a typical strength curve.

Youd and Perkins (1978) suggested an equation to approximate this strength curve,

$$\left(\frac{\tau}{\bar{\sigma}_v}\right)_{\text{strength}} = \frac{C_1}{N_E^{\;C_2}} \tag{5}$$

in which N_E is the number of applied cycles of load, and C_1 and C_2 are constants. Thus, employing Equation 5 and the definition of LPI, LPI can be related to N_E/N_L as depicted in Figure 1 and illustrated below:

$$\mathrm{LPI} = \frac{\left(\frac{\tau}{\bar{\sigma}_v}\right)_{\text{earthquake}}}{\left(\frac{\tau}{\bar{\sigma}_v}\right)_{\text{strength}}}$$

$$= \frac{\left(\frac{C_1}{N_L{}^{C_2}}\right)}{\left(\frac{C_1}{N_E{}^{C_2}}\right)}$$

$$= \left(\frac{N_E}{N_L}\right)^{C_2} \qquad (6)$$

in which N_L is the number of cycles required for failure at the applied load of $(\tau/\bar{\sigma}_v)_{\text{earthquake}}$.

The next step in formulating the prediction model is to relate N_E/N_L to the pore pressure ratio r_u. Various investigators have recommended relationships for this purpose. Seed and Booker (1970) proposed the expression:

$$r_u = \frac{\Delta u}{\bar{\sigma}_v} = \frac{2}{\pi} \text{ arc sin } \left(\frac{N_E}{N_L}\right)^{\frac{1}{2\alpha}} \qquad (7)$$

in which α is a curve-fitting parameter used to approximate laboratory pore pressure data for a particular soil. Thus, combining Equations 6 and 7, r_u relates to LPI as:

$$r_u = \frac{2}{\pi} \text{ arc sin } (\mathrm{LPI})^{\frac{1}{2\alpha C_2}} \quad ; \mathrm{LPI} < 1.0 \qquad (8)$$

Equation 8 can then be used to evaluate the expected pore pressure response at a particular site under level ground conditions as follows:

(1) Determine the Standard Penetration Test (SPT) value representing a zone within a given profile.

(2) Choose the magnitude and hypocentral distance of the design seismic event.

(3) Compute the Liquefaction Potential Index (LPI) from Equation 4.

(4) Obtain C_2 from the slope of the laboratory strength data when plotted on log-log paper.

(5) Obtain the best estimate of α to fit Equation 7 to the laboratory pore pressure data.

(6) Use Equation 8 to estimate r_u.

PRACTICAL IMPLICATIONS

The previous section presented a pore pressure model requiring the estimation of C_2 and α for a particular sand deposit. Definition of a possible range for these parameters was attempted, based on published laboratory strength and pore pressure data. Values of C_2 were estimated from laboratory strength curves suggested by various investigators for different types of tests and sands. Based on this review, values of C_2 ranged between 0.10 and 0.25, with an average value of 0.19. The larger values of C_2 corresponded to strength data obtained using torsional shear or simple shear tests.

A similar study of published excess pore pressure data plotted against the normalized number of cycles N_E/N_L yielded a range of values for α between 0.5 and 1.0. Seed and Booker (1977) recommended a typical value of α of 0.7.

Using the ranges for C_2 and α given above, together with the mean values, a plot of the pore pressure response, r_u, versus LPI is generated using Equation 8, as shown in Figure 2. The solid line corresponds to the average values of C_2 and α, and the dashed lines define the upper and lower bounds based on the upper and lower bounds of C_2 and α. This plot can be used in preliminary studies to determine the relative importance of pore pressure buildup in a particular sand deposit during a given seismic event. The procedure requires an estimation of N' and LPI (or factor of safety) for the sand.

Figure 1 demonstrates that, in general, excess pore pressure increases very slowly with increasing applied shear stress. However, it increases very rapidly with slight increases in applied shear stresses close to stresses causing liquefaction. This conclusion is consistent with laboratory observations of the excess pore pressure response in sands.

To confirm the previously-stated contention that a factor of safety against liquefaction greater than 1.0 (LPI < 1.0) does not necessarily ensure safety, the upper horizontal axis of Figure 2 has been converted to read Factor of Safety Against Liquefaction. This figure demonstrates that while a factor of safety of 1.2 to 1.3 may imply safety against liquefaction, there may be a pore pressure response of up to 50%, which when considered in soil dynamic analysis may alter the computed responses of the deposit to incoming waves and the performance of a constructed facility founded on or near the deposit. Thus, a factor of safety of at least 1.5 is recommended to ensure safety against excessive pore pressure build-up. At a factor of safety of 2.0, the pore pressure response of any sand is not expected to be significant.

Example

The pore pressure response of a typical loose sand deposit is plotted against various earthquake magnitudes. The site conditions in this example are:

(a) The water table is at the ground surface.

(b) The unit weight of the deposit is 110 pcf.

(c) SPT values range from 3 to 6 blows/ft. from a depth of 0 to 30 feet below ground surface.

Thus, the site selected for this example is comprised of a very loose sand deposit with the most unfavorable of site conditions. The corrected blow count of the deposit (using the correction suggested by Teng (1962) and shown in Figure 3) is 15 blows/ft., and the corresponding strength parameter value suggested by Yegian and Whitman (1978) is 1.0.

Figure 3 shows the pore pressure response versus earthquake magnitude, M, and hypocentral distance, R. This plot can be used in preliminary studies to determine the increase in excess pore pressure during selected design seismic events. Such a determination can be useful in other types of soil dynamic studies such as site response, stability and settlement. Furthermore, such a plot can show the sensitivity of the expected pore pressure response to the design earthquake parameters.

SUMMARY

An empirical procedure is presented to evaluate pore pressure response on level ground as a function of earthquake magnitude and hypocentral distance. The procedure is simple to apply and provides quick estimations of excess pore pressure in sands for preliminary studies.

The method also provides an opportunity for utilizing field data of excess pore pressure when observed during future seismic events to improve the prediction model proposed in this paper.

It is estimated that the procedure presented herein is only valid for level ground conditions. However, the model utilized can be readily modified to account for the influence of the presence of a structure.

The proposed model, when used with typical values of the required soil parameters obtained from laboratory data, indicates that while a site may be "safe" against liquefaction during a particular seismic event, the pore pressure response in the sand may still be significant depending upon the margin of safety provided against liquefaction. In general, a factor of safety of at least 1.5 is recommended to safeguard against excess pore pressure build-up on level ground.

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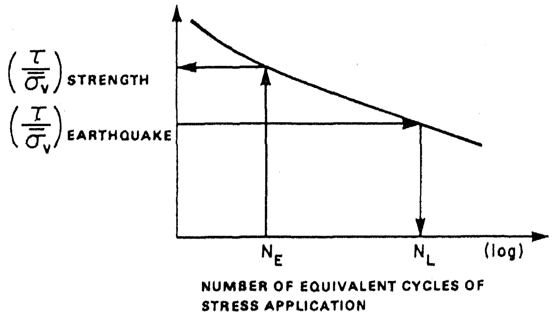

Figure 1: Typical Laboratory Normalized Strength Curve

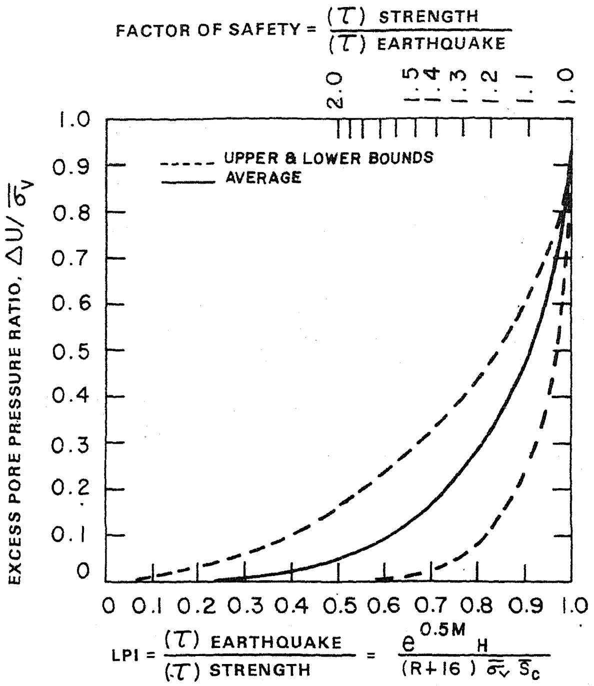

Fig. 2 Excess Pore Pressure Ratio versus Liquefaction Potential Index, LPI or Factor of Safety against liquefaction.

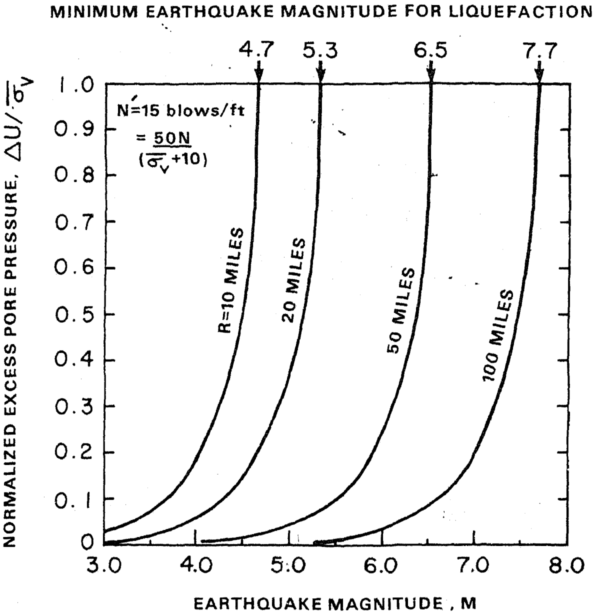

Fig. 3 Excess Pore Pressure Ratio versus Earthquake Magnitude and Hypocentral distance for the Example Site.