Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

5-2-14

PROBABILISTIC EVALUATION OF DIFFERENTIAL SETTLEMENT IN EARTHQUAKE-INDUCED LIQUEFACTION CONSIDERING SOIL-STRUCTURE INTERACTION

Achintya HALDAR[1] and Shuh-gi CHERN[2]

[1]School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.
[2]Department of River and Harbor Engineering, National Taiwan University of Marine Science and Technology, Keelung, Taiwan, R.O.C.

SUMMARY

A probabilistic model is proposed here to evaluate the damage of a structure due to earthquake induced pore pressure generation and the consequent liquefaction. The damage can be estimated in terms of differential settlement. The structural rigidity can significantly reduce the extent of damage to a structure. For a reliable assessment of the structural damage due to earthquake induced liquefaction, the structural rigidity should be considered.

INTRODUCTION

The damage associated with earthquake induced liquefaction is a major problem facing an engineer. The events of ground failure and damage to structures due to liquefaction during earthquake in China, Japan, Yugoslavia, Chile, Central America and the United States, generated a great deal of interest in the problem in the research communities. Due to the inherent complexity of the problem, research was conducted in many areas related to the liquefaction phenomenon. However, merely estimating the liquefaction potential does not sufficiently address the problem. To estimate the damage due to liquefaction, it is necessary to go one step beyond the evaluation of liquefaction potential, i.e., work must be done in the area of quantification of damage associated with liquefaction.

It has long been recognized that in a saturated sand deposit under constant volume conditions, the primary effect of the shaking is the generation of excess pore water pressure. The increse in pore water pressure will decrease the effective stress of the soil elements. The decrease in the effective stress will cause permanent settlement (Ref. 1), also referred to as cumulative or residual strain (Refs. 2,3), in the anisotropically consolidated soil elements (soil elements beneath a sloping surface or beneath an engineering facility) as the pore pressure continues to be generated due to the earthquake shaking.

Any excess residual pore water pressure generated due to the earthquake shaking will eventually dissipate along some drainage route following the earthquake. The rate of dissipation will depend on the drainage characteristics of the soil, and may range from almost instantaneous to several minutes or hours. The final results of the shaking is reconsolidated settlement of the sand.

To estimate the total settlement, it is necessary to evaluate the residual as well as the consolidation settlement, representing settlement during and following an earthquake. The total settlement or the differential settlement thus obtained can then be related to the structural damage criteria. The interaction between the structure and the soil through the redistribution of vertical loads due to uneven settlement of the foundations is also considered. Since most of the parameters in the model are random in nature, the model is developed probabilistically to quantify the uncertainties associated with the prediction of the risk of structural damage.

PROPOSED METHODOLOGY

To estimate the damage of a structure due to earthquake induced liquefaction, the generation of pore water pressure during earthquake shaking must be developed first.

The build up of excess pore water pressure in a layer of saturated cohesionless soil during an earthquake can lead to liquefaction and the consequent structural damage. Thus, in engineering designs, a careful consideration of the generation of pore water pressure in saturated cohesionless soils due to earthquake loadings is very important.

Several models have been proposed to predict the actural level of pore water pressure build up in homogeneous and nonhomogeneous soil deposits (Refs. 4,5,6). Among these models, the experimental model proposed by Seed (Ref. 6) is the most practical approach to measure the rate of generation of pore pressure. However, Seed's model was developed for isotropic soil only. It should be modified for being used for anisotropic conditions.

Pore Pressure Build Up Model for Anisotropic Deposits In most earth structures, soil element along potential failure surfaces are subjected to appreciable amount of static shear stresses. Consequently, the pore pressure on these potential failure surfaces are most closely modeled by cyclic tests on anisotropically consolidated samples.

The increase in pore water pressure due to cyclic loading can be expressed as (Ref. 3):

$$r_u = \frac{1}{2} + \frac{1}{\Pi} \mathrm{Sin}^{-1} \left[\left(\frac{N}{\bar{N}} \right)^{\alpha} - 1 \right] \tag{1}$$

where r_u= pore pressure ratio; α= a parameter whose value depends on the consolidation stress ratio K_c; N= the equivalent earthquake cycles; and $\bar{N}$= number of cycles to develop a pore pressure equal to 50% of the failure stress u_f. u_f is defined as:

$$u_f = \sigma_{3c}' [1 + \mathrm{Sin}\phi' - K_c (1- \mathrm{Sin}\phi')]/2\mathrm{Sin}\phi' \tag{2}$$

N can be obtained as (Ref. 7):

$$N = exp[(0.47083 - R_a)/0.04462] \tag{3}$$

In Eq. 3, R_a is function of consolidation ratio K_c and stress ratio SR, i.e.,

$$R_a = SR/[D_r(1 + K_c)] \tag{4}$$

Pore Pressure Induced Settlement The pore pressure induced settlement in an anisotropic sand can be evaluated from the information on the residual and consolidation settlements. Several numerical approaches have been developed to evaluate the residual settlement resulting from the cyclic loading. For simplicity, the semi-empirical model proposed by Chang (Ref. 3) is considered here and being used in this model.

Chang showed that the change in residual vertical strain $\Delta\varepsilon$ caused by a change in pore pressure Δu can be expressed as:

$$\frac{\Delta\varepsilon}{\Delta u} = \frac{\left(\frac{\sigma_d'}{\sigma_{ult}' - \sigma_d'}\right)^2 \frac{2Sin\phi'}{1-Sin\phi'} R_f + n\left(\frac{\sigma_d'}{\sigma_{ult}' - \sigma_d'}\right)\left(\frac{\sigma_{ult}'}{\sigma_3'}\right)}{K\, P_a (\sigma_3'/P_a)^n} \tag{5}$$

where $\sigma_3' = \sigma_{3c}' - u$; $\sigma_{ult}' = (2c'Cos\phi' + 2\sigma_3' Sin\phi')/[R_f(1-Sin\phi')]$; $\sigma_d' = \sigma_{1c}' - \sigma_3'$ = static deviatoric stress; R_f= the failure ratio, which always has a value less than unity; P_a= atmospheric pressure; K= a modulus number; and n= the exponent coeff.. Due to lack of space, estimation of all the parameters shown in Eq. 5 will not be discussed here.

Knowing the change in residual strain $\Delta\varepsilon$, the total accumulated residual vertical strain due to the application of N equivalent cycles of earthquake loading ε can be estimated by summing each incremental strain $\Delta\varepsilon$. Then, the residual settlement, S_d, of a sand layer of thickness h, can be evaluated as:

$$S_d = h\ \varepsilon \qquad (6)$$

The prediction of Consolidation Settlement The consolidation settlement will occur due to the dissipation of the excess pore pressure after earthquake has ceased. Assuming the sand layer is compressible and no lateral deformation is possible during the dissipation of excess pore water pressure, the consolidation settlement for the layer can obtained as:

$$S_c = m_v\ h\ u \qquad (7)$$

where m_v= the volume compressibility of the layer, which is assumed to remain constant and equal to the maximum value reached during the pore water pressure build up.

EVALUATION OF STRUCTURAL DAMAGE

The methodology described previously for the prediction of pore pressure induced settlement of structures can be applied to evaluate the structural damage.

The structural damage is estimated in terms of the induced maximum differential settlement, δ_{max}, measured from the deformed shape of the foundation after the uniform settlement and the tilt components have been removed. Fig. 1 illustrates this definition for a three-footing structure where the middle support is assumed to settle more than the exterior supports. In a symmetric case, the value of the tilt is zero and therefore, δ_{max} is simply computed as the difference between the total settlements for the central and the exterior support points. In this case, δ_{max} can be approximately defined as:

$$\delta_{max} = S_2 - \tfrac{1}{2}(\ S_1 + S_3\ ) \qquad (8)$$

where S_2, S_1 and S_3 are the total pore pressure induced settlements S $(=S_d+S_c)$ of the interior and the exterior supports, respectively.

Within a probabilistic framework, the maximum differential settlement expressed in Eq. 8 becomes a random variable denoted by Δ_{max}. For the three-footing structure, the mean and the variance of Δ_{max} are obtained in terms of the means and variances of the total settlements assuming that the settlements are independent of each other. Then

$$E(\ \Delta_{max}\ ) = E(\ S_2\ ) - \tfrac{1}{2}[E(\ S_1\ ) + E(\ S_2\ )] \qquad (9)$$

and

$$Var(\Delta_{max}) = Var(S_2) + \tfrac{1}{4}[Var(S_1) + Var(S_3)] \qquad (10)$$

Knowing the statistics of the maximum differential settlement, δ_{max}, the damage potential of a structure can be evaluated if the allowable differential settlement, δ_{all}, of the structure is given.

SOIL STRUCTURE INTERACTION

If the deformation at any point on the soil-structure interface differs from the deformation that would occur at this point in the free field if the structure were not present, there is soil-structure interaction. In the previous section,

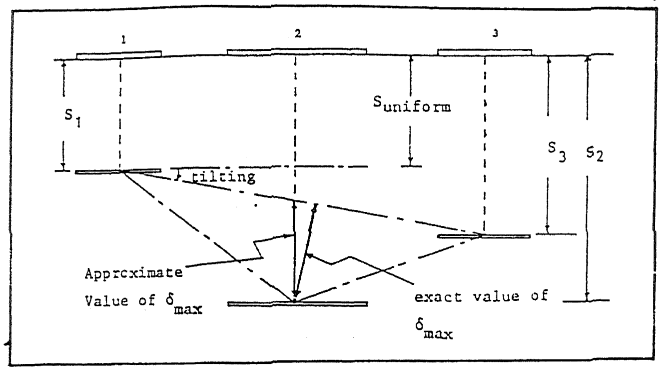

Fig.1 Definition of the Maximum Differential Settlement, δ_{max}

the loading system was idealized as a set of independent loads applied at the ground level, and the structural continuity was ignored. If a particular column is very heavily loaded, then the settlement underneath it is expected to be large. This will cause a redistribution of forces and a part of the load will be transferred to less stressed support points, thus changing the settlement profile. In some cases, the rigidity of a structure will influence its settlement characteristics.

A settlement prediction method is proposed here for structures supported on shallow foundations. Due to the complexity of pore pressure related soil-structure interaction during earthquake shaking, the method considers only the consolidation settlement after the earthquake has ceased. The interaction between the structure and the soil is accounted through the redistribution of vertical loads due to uneven settlements of the foundation. The details of this case will not be discussed here but can be found elsewhere (Ref. 7). However, the influence of soil-structure interaction will be illustrated with the help of an example as shown in the next section.

EXAMPLE

A structure with three seperated footings as shown in Fig. 2 is considered here. The structure under consideration is a symmetrically supported two-way, one-story frame building, with symmetrical loads. The foundation consists of a group of isolated footings which are designed for an allowable bearing pressure of 2000 ksf. The structure is assumed to be sitting on a level ground surface of a hypothetical site having soil properties similar to Oosterschelde sand. The site consists of seven sublayers. All the sublayers are assumed to be homogeneous.

The site is subjected to an earthquake of magnitude 7.5 for a duration of 30 seconds and an estimated acceleration of 0.20g at the ground surface. A finite element mesh consisting of forty-two quadrilateral elements are used to obtain a numerical solution. Detailed description of soil properties and footing dimensions can be read from Fig. 2.

Considering that the serviceability constraint requires limiting the maximum net slope $(\delta/L)_{max}$ to a value less than or equal to 1/300, the probability of structural damage can be expressed as:

$$P(\Delta_{max} \geqq \delta_{all}) = P(\Delta_{max} \geqq 0.8'' \mid L = 20') \qquad (11)$$

The probabilities of structural damage ($\Delta_{max} \geq 0.8''$) as function of interior footing width B are illustrated by curve (1) in Fig. 3. It shows that the probability of structural damage increases as B increases. The effect of structural rigidity on the probabilities of Δ_{max} exceeding 0.8 in. is also presented in Fig. 3. As expected, the probability value is reduced if the structural rigidity is considered.

EFFECT OF SOIL CONDITIONS ON STRUCTURAL DAMAGE

To study the effects of various soil characteristics on the generation of the pore pressure and the consequent structural damages, different analyses are performed by varying one of the soil characteristics at a time while keeping the others constant.

Effects of Soil Compressibility m_v It is found that pore pressure increases as m_v increases. In the same way, the settlements beneath interior and exterior footings also increase, resulting in the increase of the probability of structural damage.

Effects of Relative Density D_r Relative Density, D_r, can considerably affect undrained behavior of a saturated sand deposit subjected to earthquake loadings. Increasing initial relative density will increase the cyclic shear strength, reduce the excess pore pressure and the possibility of liquefaction. More importantly, as relative density increases, the earthquake induced settlement decreases, thus reduces the possibility of structural damage. On the other hand, decreasing relative density will increase the possibility of structural damage.

Effects of Soil Stratum The strata of sand deposits may affect the generation of pore pressure when subjected to earthquake loadings. If loose sand layers exist between two dense layers, larger pore pressures are generated in the loose layers that are confined in the two dense layers. Thus, the rate of the pore pressure generation in the loose layer is increased. As a result, a large amount of settlements in the foundations are observed, and the building is damaged seriously.

Effects of Gravel Drain The presence of the gravel drains had a significant effect on reducing the pore pressure development in the sand deposits. Because the pore pressure near the drains can dissipate more quickly to the ground surface, the pore pressures generated in the sand deposits with drains are smaller.

If the top layer of the example considered here is replaced by a pervious gravel layer, it is found that only a small amount of pore pressure are generated. Therefore, the settlements are reduced and the structural damage may be prevented.

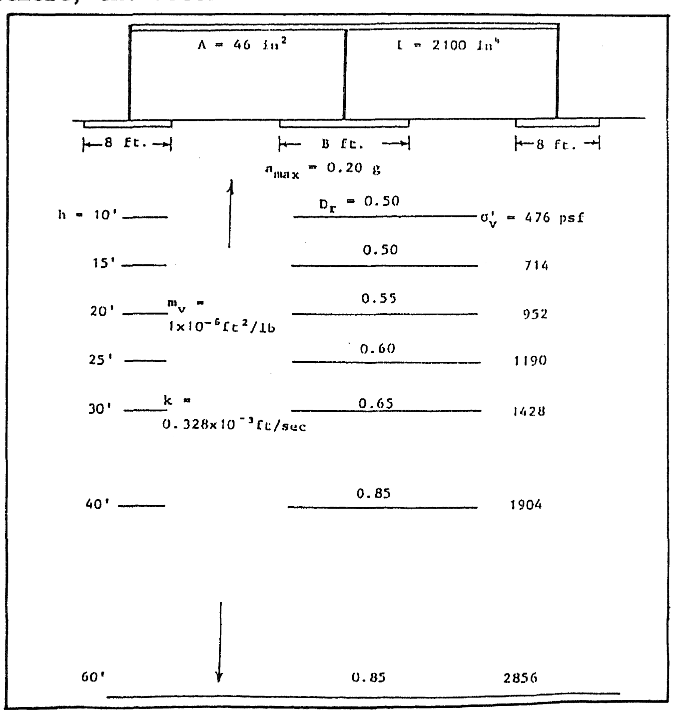

Fig. 2 Spread footing foundation and Soil Strata

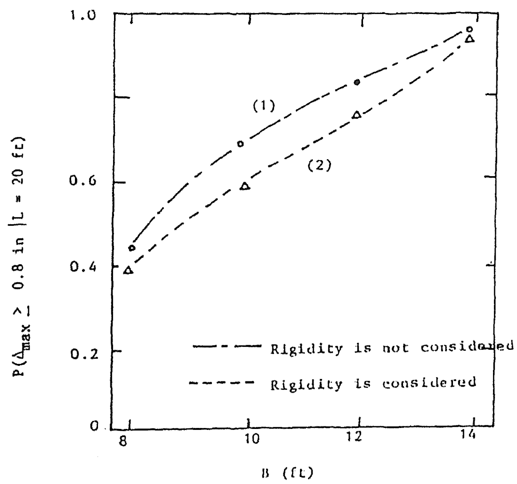

Fig. 3 Probability of Structural Damage as Functions of Interior Width B

ACKNOWLEDGEMENT

This material is based upon work partly supported by the National Science Foundation under Grants No. CEE-8312181, MSM-8352396, MSM-8544166, MSM-8644348 and MSM-8746111. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the writers and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1. Bouckovalas, G., Whitman, R. V., and Marr, W. A., "Permanent Displacement of Sand with Cyclic Loading," J. of Geot. Eng. Division, ASCE, Vol. 110, No. 11, 1606-1623, (1984).
2. Hadge, W. E., and Marr, W. A., "A Relationship Between the Drained and Undrained Cyclic Behavior of Sand," Research Report R79-23, MIT, (1979)
3. Chang, C. S., "Residual Deformation of Undrained Samples During Cyclic Loading," J. of Geot. Eng. Division,ASCE, Vol. 108, No. GT4, 637-646, (1982).
4. Lee, K. L., and Albaisa, A., "Earthquake Induced Settlements in Saturated Sands," J. of Geot. Eng. Division, ASCE, Vol. 100, No. GT4, 387-406, (1974).
5. DeAlba, P., Chan, C. K., and Seed, H. B., "Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests," Earthquake Engineering Research Center Report UCB/EERC75-14, University of California, Berkeley, (1975).
6. Seed, H. B., Martin, P. P., and Lysmer, J., "Pore-Water Pressure Changes During Soil Liquefaction," J. of Geot. Eng. Division, ASCE, Vol. 102, No. GT4, (1976).
7. Haldar, A., and Chern, S., "Probabilistic Analysis of Pore Pressure-Induced Damage Potential for Structures Subjected to Earthquake Motions," Technical Report SCEGIT-86-103, Georgia Institute of Technology, (1986).