A PROCEDURE FOR EVALUATION OF DIFFERENTIAL SETTLEMENTS OF BUILDINGS DURING EARTHQUAKE

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SUMMARY

A procedure for estimating the differential settlements of buildings on weak soil foundation during earthquake is presented. The procedure is run in three stages. First, the deformation of each node in the soil layer due to the gravity force is obtained by using the static FEM. The second stage is to perform another static analysis, using reduced values of a modulus in the elements. The reduction of the modulus of each element is related to seismic loads and depends on the dynamic stress history in the elements, which can be obtained by using dynamic FEM. The third step is to calculate the difference between the deformations obtained from the second and first steps and then the displacement of each node in the soil foundation is attained. The key in the analysis is to present a residual strain potential suitable for the irregular loads. The residual strain potential determines the reduced modulus in the elements due to the softening of the soil caused by the earthquake. The results presented in the paper indicate that the asymmetry and irregularity of the earthquake loads can play an important role in the uneven residual deformation of the soil foundation, and the differential settlements of the buildings caused by the asymmetry and irregularity of the seismic loads may be still remarkable even for the symmetrical buildings on the uniform soil layer.

INTRODUCTION

It has been recognized that the buildings on the weak foundations tend to settle when the ground is subjected to earthquakes. It also has been found that the vertical settlements are usually not equal in the two sides of the foundation of the buildings. Only remarkable uneven settlement can cause the obvious building damages such as inclination of the buildings and crack in the wall of the buildings. However, the methods presented so to solve the problem generally are suitable for evaluating the constant settlements representing an average deformation of the buildings due to earthquake.

There may be misunderstanding for the reason of the differential settlement of buildings under earthquake loads. Generally, the reason for the uneven permanent deformation of the foundation below the buildings is regarded as the asymmetry of the buildings and the non-uniform distribution of the soil layer. However, except of the long and large structures such as bridges, the length or width of the common buildings is not very large, and the anisotropy of the soil layer and the asymmetry of the buildings are generally small.. It is impossible to refer all the building damages related to the different permanent deformation of the foundation to the strong nonuniformity of the soil and buildings. Therefore, besides of the condition of the soil and building, the effect of the asymmetry and irregularity of seismic ground motion on the different settlements of the buildings should be investigated.

Serff et al (1976) developed a method for calculating the earthquake-induced deformations of an earth dam. Haldar and Chern (1988) presented a model to evaluate the differential settlement in earthquake-induced liquefaction. However, the formula used in their models for estimating the residual strain of the soil element is

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only suitable for the uniform cyclic loading. The effect of the time-varying seismic loads can not be included in the results. In the present paper, the residual strain potential for the irregular stress loads is proposed and applied to calculate the reduced modulus in the elements due to the softening of the soil caused by the earthquake.

MODEL AND PROCEDURE

Model

The cross-section of the two-dimensional model to be analyzed is shown in Fig.1. It represents the non-linear soil layer on which a building exists. The seismic waves vertically transmit from the bedrock.

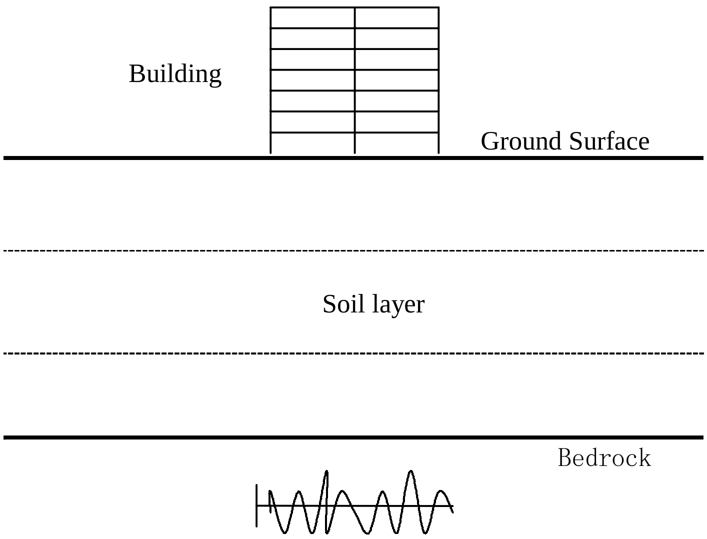

Fig.1 Soil Layer with a Building

Residual Strain Potential of Soil Element

The key point in the paper is to present the residual strain potential of the soil element under the excitation of the random loads. The permanent deformation of a soft soil element due to an uniform stress load can be evaluated using the dynamic triaxial shear tests. The semi-empirical formula proposed in Ref.7 is written here

$$\bar{\varepsilon}_p = 10\left[\frac{1}{c_5}\cdot\frac{\bar{\sigma}_d}{\sigma_3}\right]^{\frac{1}{s_5}}\left(\frac{N}{10}\right)^{-\frac{s_1}{s_5}} \qquad (1)$$

where

$\bar{\varepsilon}_p$: residual strain potential;

σ_3: confining stress;

N: the equivalent number of constant amplitude cycles representing the random earthquake loads;

$\bar{\sigma}_d$: the equivalent constant amplitude of the random stress cycles;

c_5, s_1, s_5: the coefficients determined by the soil type and consolidation ratio of the soil.

Using the triaxial tests, Eqn.1 has been checked and proved to be correct for the uniform cyclic loads. To obtain the residual strain potential under the random cyclic loading, the irregular loading is first divided into a series of cyclic loads with different amplitude as shown in Fig.2. Then, the incremental method is used here

$$\varepsilon_p^i = \varepsilon_p^{i-1} + \Delta\varepsilon_p^i \qquad i=1,2,\cdots\cdots,M \qquad (2)$$

where

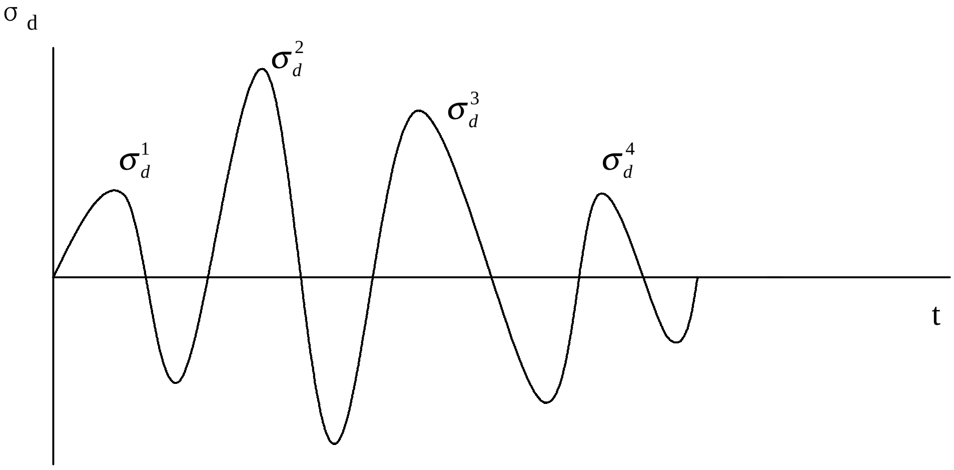

Fig.2 A Series of Cyclic Loads with Different Amplitudes

ε_p^i: the accumulative residual strain after the *i* th stress cycle;

ε_p^{i-1} : the accumulative residual strain after the i-*1*th stress cyclic load, ε_p^0=0;

M: the total cyclic number of the random stress loads;

$\Delta\varepsilon_p^i$: t he residual strain produced by the i th stress cycle, which can be obtained by

$$\Delta\varepsilon_p^i = \left(\frac{\sigma_d}{\sigma_3 c_5}\right)^{\frac{1}{s_5}}\left(-\frac{s_1}{s_5}\right)\left(\frac{i-1}{10}\right)^{\left(-\frac{s_1}{s_5}-1\right)} \tag{3}$$

$\Delta\varepsilon_p$ is the increment of the residual strain caused by σ_d, representing the partial derivative of $\bar{\varepsilon}_p$ with respect to N, and

$$\Delta\varepsilon_p = 10\left[\frac{1}{c_5}\cdot\frac{\sigma_d}{\sigma_3}\right]^{\frac{1}{s_5}}\left(\frac{1}{10}\right)^{-\frac{s_1}{s_5}} \tag{4}$$

In Eqns. 1and 2, the effect of the frequency of the stress loading is not taken into account, because there are a lot of results (see Ref.8) proving that the effect of the incident frequency can be negligible generally.

When the uniform load is applied to Eqn.2, the residual deformation calculated by Eqn.2 is the same as the results by Eqn.1. For the random loads, Eqn.2 can be checked using the results obtained by other researchers. Some examples of comparison are given here. Using the irregular stress loads, the dynamic triaxial tests were performed by Ishihara et al (see Ref.9). For the stress history, both types of tests (CM-test and EM-test) were carried out in the tests. CM-test means that the maximum peak of the stress history used in the tests can be attained when the triaxial loading piston reaches the lowest position. EM-test means that the maximum peak stress is oriented so that the maximum peak is executed at the highest position of the loading piston in the tests. In the present paper, Eqn.2 is used to calculate the residual strain potential for the similar soil as those in Ishihara's paper under the same stress loads as those in Ishihara's paper. The calculated results by Eqn.2 are shown in Figs.3 and 4. Fig.3(a) demonstrates the CM stress load history, and Fig.3(b) and (c) show the residual strain history when the maximum stress amplitude is 0.39 kg/cm^2 and 0.6kg/cm^2 separately. Fig.4(a) illustrates the EM stress load history, and Fig.4(b) and (c) show the residual strain potential corresponding to the maximum stress amplitudes of 0.38kg/cm^2 and 0.56kg/cm^2 separately. Comparing Figs.3(b), 3(c), 4(b) and 4(c) here with Figs.3(b), 3(c), 4(b) and 4(c) in Ishihara's paper respectively, it has been found that the results by Eqn.2 agree with these by triaxial tests both in the general trend and in the final values of the residual strain potential. The figures also indicate that the asymmetry of the stress loads can takes significant effect on the values of resident strain potential. As shown in the figures, the final permanent strain of the soil are 0.192%, 1.95% for CM test, and 0.333%, 2.68% for EM test. 65% and 31% difference of permanent displacements of the soil are caused between CM and EM loading tests.

The Equs.1 and 2 can only be used for the soft clay soil. For the saturated sand foundation, the derivation of a formula of the residual stain potential suitable for random stress force is more difficult. However, the same idea as that for the soft soil in the paper can also be employed for the sand soil.

Analytical Procedure

To calculate the differential settlement of the building in the model as shown in Fig.1, a procedure can be adopted as follows:

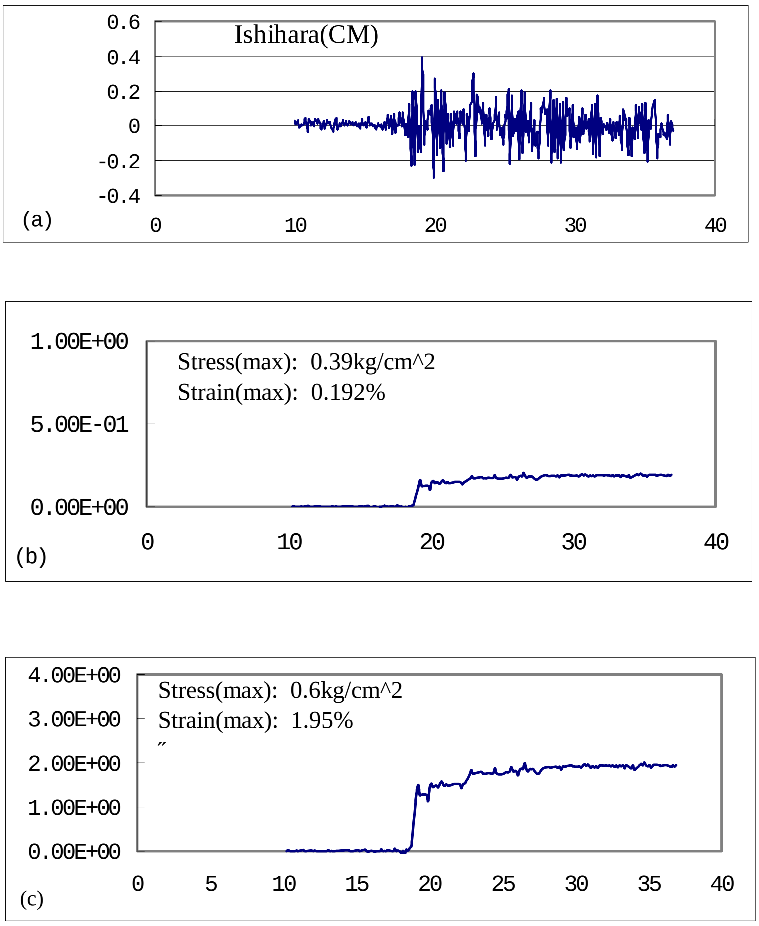

Fig.3 Residual Strain Potential Calculated by Eqn.2 under CM Load

(1) Using the non-linear static FEM and the iterative computation, the distribution of the static stresses in the soil layer and the initial values of the modulus, E_i, are determined. The deformation of each node in the soil elements due to the gravity force of the buildings and soil layer is recorded and stored for later use. The calculated deformations are only reference deformation and not representative of any actual pre-earthquake deformation.

(2) The second stage is to perform another static analysis, using reduced values of a modulus in the soil elements. The reduction of the modulus in the elements represents the effect of seismic loads. The reduced modulus of each element, E_s, can be expressed as

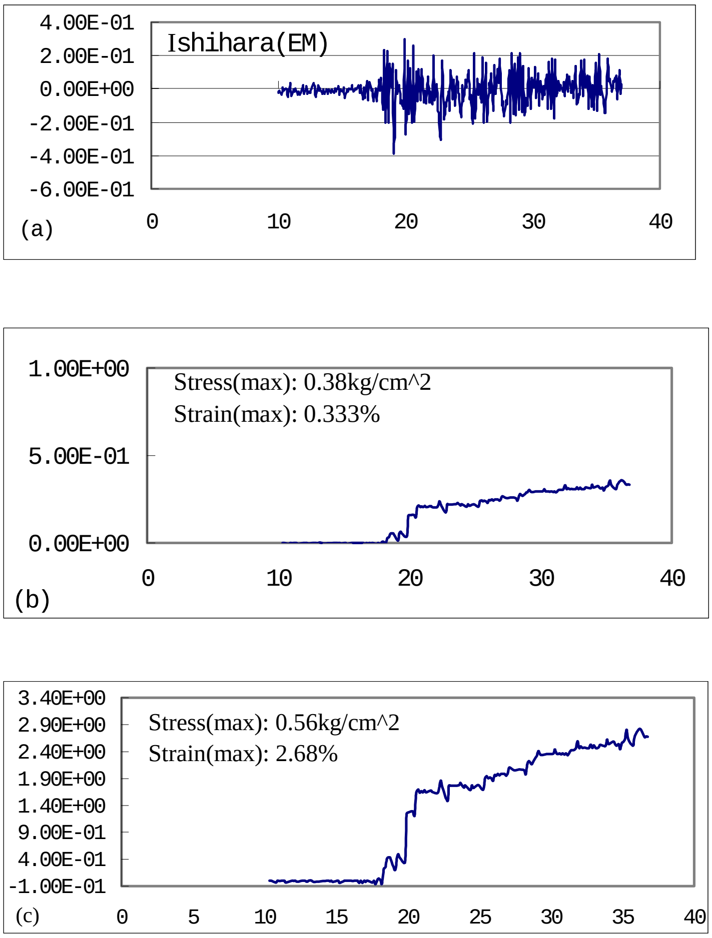

Fig.4 Residual Strain Potential Calculated by Eqn.2 under EM Load

$$E_s = \left(\frac{1}{E_i} + \sum_{j=1}^{M} \frac{1}{E_p^j}\right)^{-1} \tag{5}$$

The E_p^j represents the reduced modulus caused by the j th stress cycle, which can be determined by

$$E_p^j = \frac{\sigma_d}{\Delta \varepsilon_p} \tag{6}$$

where, σ_d can be determined by dynamic stress history in the elements using the dynamic FEM and $\Delta \varepsilon_p$ can be obtained from Eqns. 3 and 4.

(3) The third and final stage is to calculate the difference between the deformations obtained from the second and first stages and present the displacement of each node in the soil foundation. Both the history and the final values of the permanent settlement of the buildings under seismic loads are then obtained.

EXAMPLES AND DISCUSSIONS

The building on the surface of the weak ground tends to settle and the settlement generally is unequal in the two sides of the foundation of the buildings. The value of the differential deformation depends on the pattern of the seismic ground motion, the form and weight of the building, as well as the property and distribution of the soil layer. Actually, the procedure proposed in the paper can be used in any complicated case of the soil and building. However, to place the emphasis on the effect of the seismic loads, the symmetrical building and uniform soil layer are chosen in the following calculation.

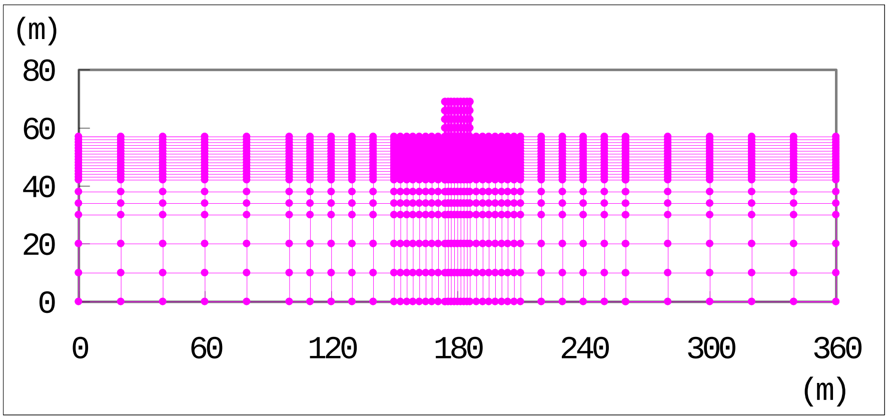

Fig.5 Finite Element Division

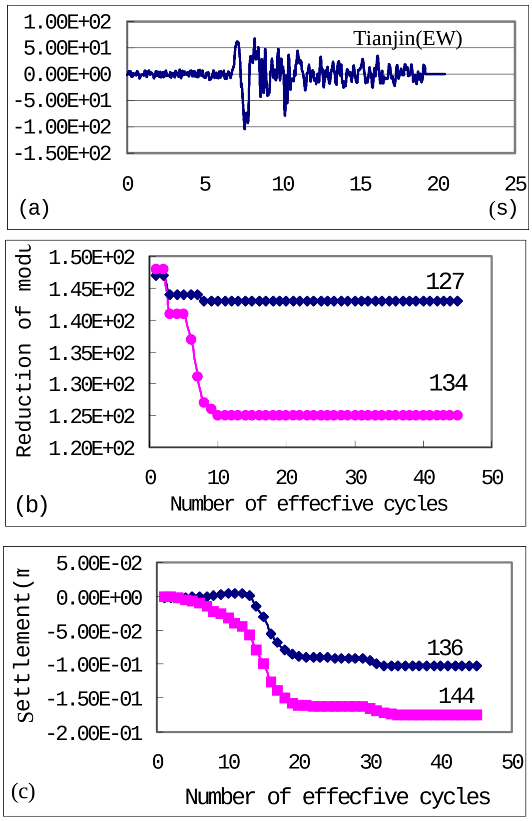

Fig.6

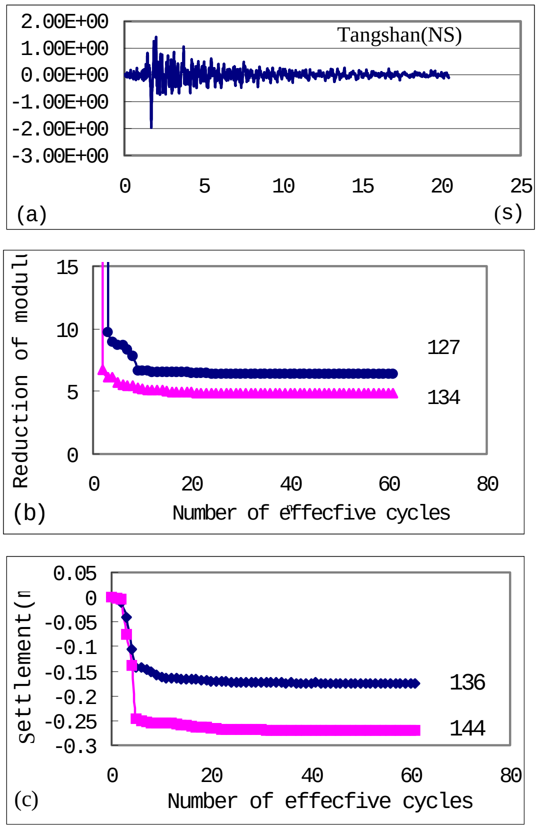

Fig.7

The model of calculation and division of finite elements to be analyzed are shown in Fig. 5. It represents a soft soil layer on which a building with 4 stories and width of 12m exists. The soft soil layer has thickness of 57m. The soil property is chosen nearly as the same as that in the Tianjin City in China. The differential settlements of the soil foundations occurred, and the buildings in Tianjin City have been heavily damaged in Tangshan Earthquake in 1976.

Two acceleration histories recorded in situ are employed as input waves, as shown in Figs. 6(a) and 7(a), separately. One is recorded at the Tianjin Hospital in aftershock of Tangshan Earthquake. Another is recorded at the Tangshan Airport in the aftershock of Tangshan Earthquake. The peaks of both acceleration recordes are adjusted to 0.2g at the ground surface of the soil layer. The reduction of the modulus of two elements is shown in Figs. 6(b) and 7(b) separately for the incidence of the two waves. The abscissa in the Figs.6(b), 6(c),7(b) and 7(c) is the number of the effective cycles. Because small amplitudes in the acceleration history do not effect on the reduction of the modulus, the small amplitudes of the acceleration history are removed from the calculation for saving the time of the calculation. The soil elements, 127 and 134, are just located below the two sides of the building. The permanent displacements of the two notes, 136 and 144, just being below the symmetric two sides of the building, are illustrated in Figs. 6(c) and 7(c), separately for the two incident waves.

The results from the figures indicate that the reduction of the modulus and the settlement are not constant in the two sides of the buildings. The vertical permanent displacement of the building is 0.1m in one side and 0.17m in another side for inputting the Tianjin seismic record. The differential settlement in the two sides is 0.07m and 52% difference occurred comparing with the average settlement of 0.135m. For inputting the Tanshan earthquake record, the deformations in the two sides in the soil foundation below the building are 0.17m and 0.28m separately. The differential settlement is 0.11m and 49% difference appeared comparing with the average value of 0.225m. The reason for the differential settlements of the building is that both the peak amplitude and the history of the dynamic press stresses in the two sides of the soil foundation are not same because the seismic ground motion is irregular and not symmetric. As a result, the values of the reduced modulus are not equal in the two sides of the soil layer near the building, and then, uneven deformation in the soil foundation appears.

CONCLUSIONS

The purpose of the paper is to present a procedure for estimating the earthquake-induced differential settlements of buildings on weak foundation. The procedure is divided into in three steps. The most important point in the analysis is to propose the residual strain potential for the random seismic loads. Then, the asymmetry and irregularity of the earthquake loads on the uneven settlements of the buildings can be considered more reasonably.

Generally, three basic factors, including the type and form of the building, the property and distribution of the soil layer, and the amplitude and form of the seismic ground motion, all affect the differential settlements of the foundation below the buildings. The uneven deformation of the soil layer may result from one of the factors or the combination of the more factors. The important work is to distinguish which factor or what kind combination of the factor play the dominant role in determining the unequal settlements of the foundation. The results in the paper show that the irregularity and asymmetry of the seismic loads can produce an important influence on the differential deformation of the buildings in the common cases. The results also indicate that, even for the uniform soil layer and symmetrical building, the differential settlements of the foundation may be still remarkable and the asymmetry and irregularity of the earthquake loads play a dominant role in this case.

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