ANALYSIS OF EARTHQUAKE INDUCED FOOTING SETTLEMENT

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SUMMARY

The magnitude of footing settlement induced during earthquake depends significantly on the in situ static shear stress in soil prior to the application of earthquake induced cyclic stresses. The behavior of the pore pressure build-up accompanied with the deformation due to cyclic loading can be modeled by either a phenomenological model or by an effective stress strain model. This paper describes a finite element procedure for the analysis of the undrained footing settlement due to pore pressure generation during earthquake. This methodology can potentially be applied to other problems such as earthquake induced deformation of dams, slopes or settlement of raft foundations.

INTRODUCTION

In dry sand, earthquake induced footing settlement is caused by a reduction of voids due to a rearrangement of sand particles under cyclic stresses. In saturated sand, the voids are filled with water which is relatively incompressible, thus a change of void volume has to be a result of water flowing out of the soil. However, due to the pore pressure generated during an earthquake, effective confining stress is reduced in the soil and shear deformation may occur even though the soil remains in an undrained condition. Conceptually the cyclic stress induced deformation in a saturated sand can be divided into three components:

1) the accumulated residual undrained shear deformation
2) the residual shear deformation due to the generation of pore pressure, and
3) the additional volume change due to excess pore pressure dissipation.

Although the three components occur simultaneously during an earthquake, it is a good approximation to assume the undrained deformation of the first two components occurs during the earthquake and the third component of dissipation settlement occurs after the earthquake. Analysis procedure described in this paper is focused on evaluating the undrained footing settlement on saturated sand due to earthquake loading.

FINITE ELEMENT ANALYSIS FOR EARTHQUAKE INDUCED SETTLEMENT

A finite element method is adopted for the analysis of footing settlement. This analysis procedure includes the following stages:

1) Estimate the cyclic shear stress in each soil element induced by earthquake loading.

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2) Use the estimated cyclic shear stress to evaluate the pore pressure generation and residual strain for each soil element.
3) Apply the pore pressure and residual strains for each soil element to the complete finite element mesh to estimate the over all footing settlement.

Because the dynamic stress induced by the inertia force has been estimated in the first stage analysis, the third stage analysis can be simplified to neglect the inertia force and thus is a quasi-static analysis. These three stages of analysis are described in the following:

Evaluation of Dynamic Stress Induced by Earthquake

The stresses induced by earthquake waves in soil element are complicated in nature. As schematically shown in Fig.1, the magnitude and the distribution pattern of the dynamic stresses are influenced not only by the shear wave propagated upward from the base rock but also by the interaction between the footing and the soil. Earthquake loading generally cause footing rocking, sliding and vertical vibration. The dynamic stresses in the soil beneath the footing would be influenced greatly by the dynamic response of the building especially if the building weight is heavy.

However to reduce the problem to a manageable size, the effect of interaction between building and soil is neglected and the dynamic stresses in the soil is primarily caused by the shear wave. The only effect of the building on the dynamic stress is the static stress in the soil caused by the building.

The maximum dynamic shear stress on the horizontal plane of a soil element induced by earthquake shear wave can be estimated from a knowledge of acceleration specified on the ground surface.(Ref.1)

By using this method, the maximum dynamic shear stress in the soil beneath a footing can be approximately estimated. The calculated dynamic shear stress in the soil beneath a footing is shown in Fig.2.

Evaluation of Pore Pressure Build-up and Residual Strain of an Undrained Soil Sample due to Cyclic Shear

There are two approaches to evaluate the pore pressure build-up and the residual strain due to cyclic shear. The first one is a phenomenological approach and the second is the effective stress approach.

1) Phenomenological Approach

In the first approach, the rate of pore pressure build-up and the rate of residual deformation can be correlated to the initial stress state of the soil, the applied cyclic stress, and the number of cycles from a series of experimental tests. An equation of an arcsine function has been used to describe the rate of pore pressure build-up due to cyclic shear applied to an isotropically consolidated triaxial sample or a simple shear sample without a presence of static shear.(Ref.2) This equation was then modified for estimating the rate of pore pressure build-up in an anisotropically consolidated triaxial sample, where there is a presence of static shear stress. (Ref.3) And the equation was further extended to a

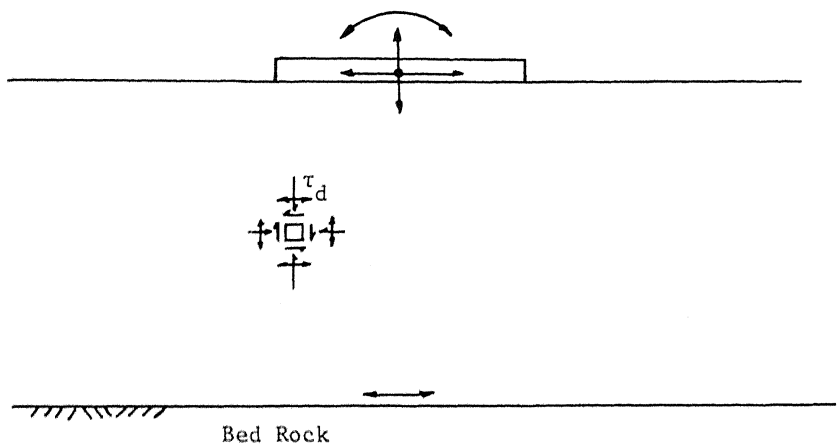


Fig.1 Earthquake Induced Stresses in a Soil Element under a Footing

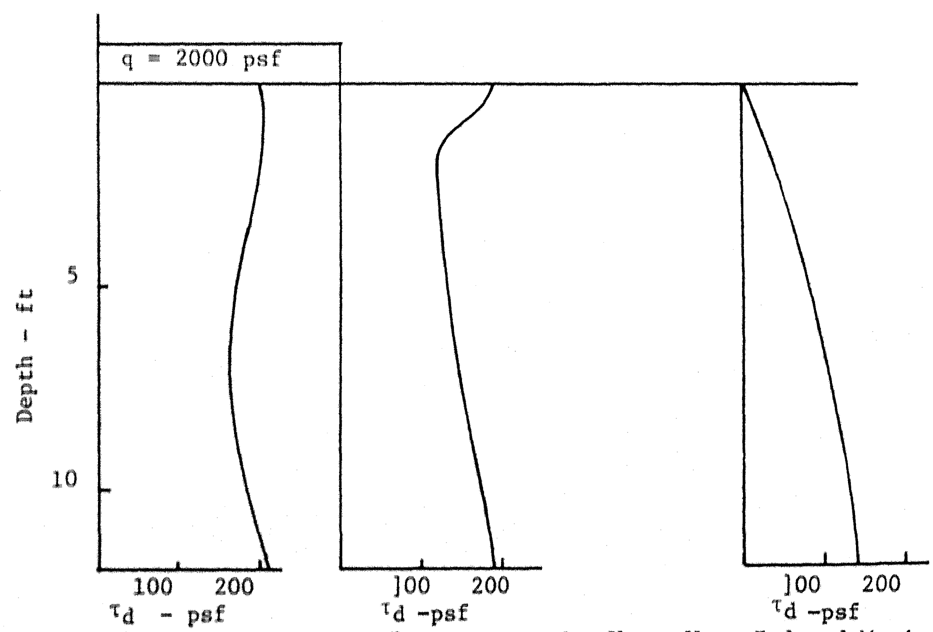


Fig.2 Effect of Footing Pressure on the Shear Wave Induced Maximum Dynamic Shear Stress along Depth

a more general form applicable to samples with higher anisotropical consolidation ratios. (Ref.4) As described in Ref.4 there are six parameters involved in this equation. Although this approach does not provide an insight into the mechanism, but rather as a curve fitting procedure, it is direct and practical.

The residual deformation of an undrained triaxial sample is primarily caused by the reduction of effective stress due to the pore pressure generation. Using the hyperbolic relationship between the deviatoric stress and the vertical strain and considering the effect of effective confining stress reduction, an equation was derived for estimating the residual strain due to cyclic shear. (Ref.5) Fig.3 shows a comparison between measured experimental results and predicted results using the phenomenological approach.(Ref.6) The measured material is a fine round quartz sand with shell fragments. Three tests were performed on the sand with same relative densities under different initial anisotropical stress states and different applied cyclic stress conditions. The predicted results were calculated by using one set of parameters for all three test conditions. The agreement was reasonably good.

2) Effective Stress Approach

The second approach is to use an effective stress model to estimate the residual pore pressure and residual strain. One of the earliest effective stress stress strain model was developed by Finn, Lee and Martin (Ref.7) for simple shear condition. Recent development in plasticity models and Endochronic Theory (Ref.8) has shown a greater applicability to model cyclic soil behavior. However these models do not take into consideration the microstructure of sand. Therefore a nonassociated flow rule or equivelent assumptions are necessary in order to correctly model the volume change behavior under cyclic shear. It is difficult to find a function of a nonassociated flow rule that is general enough to represent soil behavior under a wide range of stress conditions. Thus an model was developed by the author for modelling cyclic stress strain relationship taking into account the microstructure of sand.(Ref.9) The constitutive model was developed based on the sliding mechanism of two contact particles and the density function of the contact normals for an assembly of particles, which considers the following features: 1) volume change induced by shear sliding of particles, i.e. dilatancy behavior. 2) the stress induced anisotropy of the packing structure and 3) the effect of the packing structures on deformation behavior.

The model has been verified by comparing the predicted results and measured experimental results which include drained cubical triaxial tests with different intermediate principal stress, drained and undrained cyclic triaxial compression tests, cyclic isotropic compression tests, and drained cyclic simple shear tests. The detailed description of the constitutive model can be found in Ref.9.

The effective stress strain approach provides an insight of the deformation and pore pressure generation mechanism however the required number of parameters are relatively large and the computation involved in the prediction is more complicated.

Estimation Of the Footing Settlement Using Numerical Method

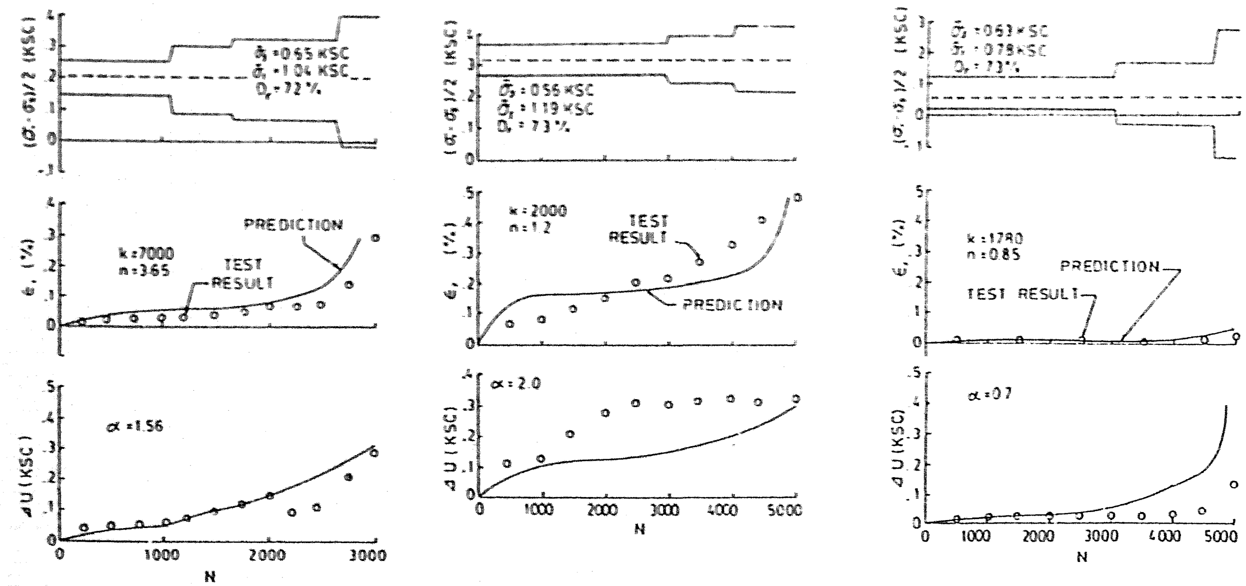


Fig.3 Comparison Between Predicted and Measured Pore Pressure Build-up and Residual Deformation in Triaxial Samples under Variable Cyclic Loading (Ref.6)

A plane strain finite element computer program was used for estimating the footing settlement due to earthquake induced cyclic shear. The computer program is a coupled stress-flow finite element program modified from a computer program CON2D originally developed for the purpose of evaluating deformation and pore pressure generated in earth dams during construction. (Ref.10) The residual deformation and the pore pressure build-up versus time during the earthquake for each element in the mesh estimated from the analysis in stage 2 can be used as input data to this computer program, and the computer program computes the deformed mesh for each time step due to the pore pressure generation in each soil element. The finite element method considers the interaction between stress and flow, the total stress change in each element and the water flow in the soil region. The effective stress strain model is incorporated in this finite element program. However the inertia and damping in the soil mass are not considered, since the cyclic stress is computed separately in the stage 1 analysis. The detailed description of this finite element computer program can be found in Ref.11.

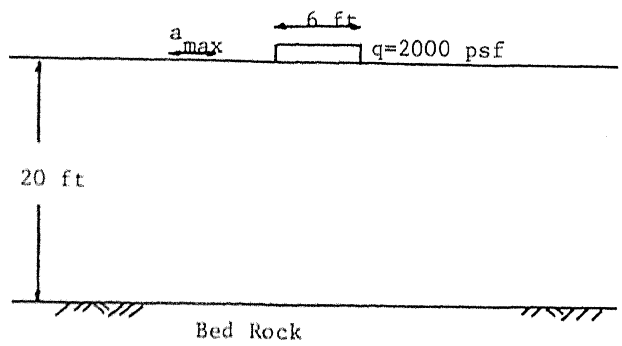
Examples of using this method for estimating footing settlement are shown in Fig.4. Two cases were considered: one is for a relative density of 50% and another 70%. The corresponding material parameters were estimated and the footing settlement computed for maximum surface acceleration equal to 0.2g. The assumed acceleration time history is sinusoidal and the number of cycles used were 5,10, and 15, corresponding to earthquake magnitude 5,6 and 7. The surface pressure caused by the footing load is assumed 0.2 tsf. The footing settlement induced by the earthquake is divided by the static footing settlement and plotted in Fig,4, against the magnitude of surface acceleration.

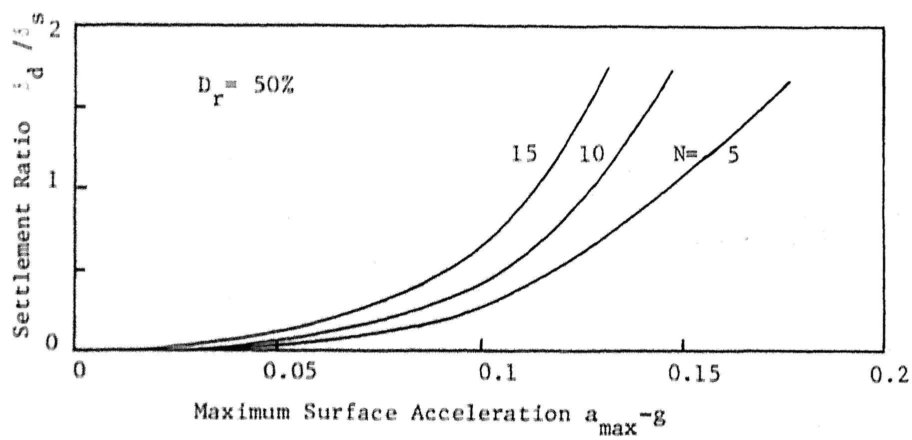
DISCUSSION

The undrained footing settlement computed by this method increases as the surface acceleration increases however the relationship is not linear. As the acceleration is small the undrained footing settlement is insignificant. On the contrary, as the acceleration is large, approaching to the free field acceleration that induces liquefaction, the undrained footing settlement increases significantly. Thus, even though under the same magnitude and intensity of earthquake, the soil beneath a footing does not liquefy as easily as that in the level ground because of the increased effective overburden stress due to footing load, the footing may still suffer large undrained settlement such that it would not be considered as safe.

Magnitude of the undrained footing settlement is directly related to the pore pressure generated during the earthquake. The characteristic shape of the pore pressure build-up curve versus number of cycles indicates a significant change in the rate of pore pressure build up as soil approaches liquefaction. The results on finite element analysis also show that the number of cycles corresponding to the earthquake magnitude as well as the soil density may greatly influence the undrained footing settlement.

The earthquake induced footing settlement considered in this paper does not include the effect of interaction between building and soil. For heavy buildings the undrained settlement would be higher than those





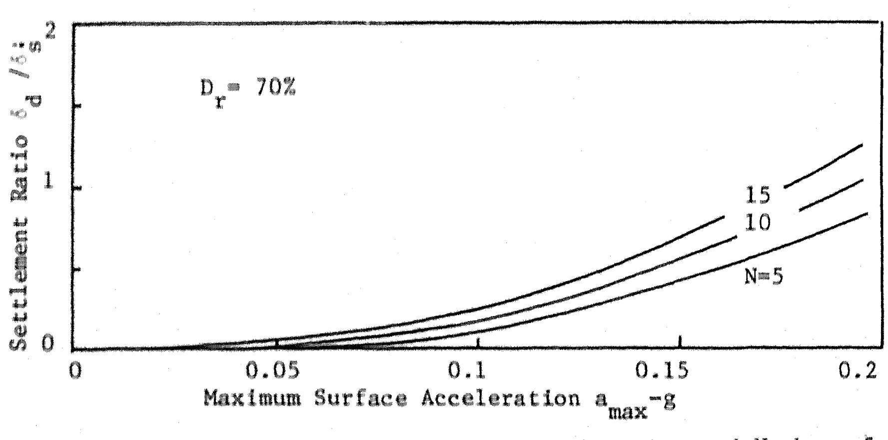


Fig.4 Effect of Maximum Surface Acceleration and Number of Cycles on the Earthquake Induced Undrained Footing Settlement

computed by this method.

Earthquake induced building settlement after soil liquefaction has been reported in some literature, however building settlement preliquefaction has not been given much attention. Experimental work and field measurement are needed for further understanding of the problem.

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