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THE DYNAMIC EFFECT OF PORE-WATER-PRESSURE VARIATION ON THE FOUNDATIONS IN MAN-MADE DEPOSITS

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SUMMARY

In this study the dynamic behavior of foundations located in the reclaimed lands near coastal area was investigated. It was found that during the 1999 Chi-Chi earthquake (magnitude of Richter's scale reaches 7.3) a series of wharves of caisson type located in the harbor area were suffered severe damage. According to the investigation, the area of the harbor having serious foundation-damages is mostly the reclaimed land. The investigation also found the associated structural damage, landsite settlement and sand-boils induced from the possible liquefaction of the soil. Most of all are the seriously displaced caisson quay-walls, the infrastructures for the wharves. The distorted caissons ranged more than 1 km long and 1.5 meters away from the original alignment. In the reclaimed landsite among many sand-boil holes some larger ones are more than 4 meters deep. Comparing to 1995 Kobe earthquake the damages in the harbor area seemed unreasonably drastic. Therefore, it is interested to know except for the influence of basic properties of the soil what really causes those serious damages in this area.

For the wharf damaged due to infrastructure failure, factors considered may include the enlargement of ground motion during transmission of the seismic waves, the liquefaction phenomenon and pore-water pressure variation, the interaction effect between the structure and the soil and other influences of reclaimed land in the area. Due to the complexities of all kinds of factors, this study focused on the dynamic behavior of the foundation subjected to seismic waves while the soil-structure interaction is ignored. In the analysis, the transmission of the seismic waves mostly the P-wave and S-wave from underground source through a multi-layer of soil of generally the kind of man-made subjected to variation of pore-water pressure is taken into accounts. Based on the experimental data from cyclic loading tests on the liquefaction and settlement including the variation of pore pressure ratio and axial strain percentage related to the loading cycles and volumetric strain percentage to the pore pressure ratio, the analytical model for the foundation located in the reclaimed soil subjected to the pore-water pressure variation is established.

INTRODUCTION

Chi-Chi earthquake hitting the central Taiwan on September 21st 1999 is one of the most disastrous in this decade. The magnitude of Richter's scale of Chi-Chi earthquake reaches 7.3 and the acceleration of ground motion is up to 560 cm/s^2 or 571 gal. This earthquake claimed more than 2,500 lives and over twenty thousands of houses and buildings were destroyed or seriously damaged. It hit areas more than three hundred km away from the epicenter such as Taipei metropolitan area, where several high-rise buildings were collapsed. The roads and bridges around the epicenter were mostly destroyed.

Many structures were suffered serious damages due to the collapse of the foundation, the land sidings or footing failure. Sand boils could be found along the riverside and coastal area, where generally had reclaimed land. Particularly in the Taichung Harbor, some holes induced from this strong ground shaking measured several meters wide and deep. There are strong evidences showing that soil liquefaction and the rising up pore water pressure played important role for these serious damages. Therefore, it is interested to know the behavior of the pore water pressure during the earthquakes, particularly the variation of pore pressure to the dynamic response of foundations even though it is well known that it is the main reason causing soil liquefaction.

For the study of the pore water pressure influence on the foundation, most are focused on the critical state of the soil reaching the liquefaction state and the parameters of the soil that may affect liquefaction potential. However, very few researches are concerned about the influence of pore water pressure on the dynamic behavior of the soil foundations, particularly, the process of the rising-up of pore pressure to the response of the soil foundations. Therefore, this study is focused on the relationships between rising-up process of the pore water pressure and the response of the soil foundations subjected to earthquake-like forces.

In this study, firstly an appropriate model that may accurately and yet simply enough describe the dynamic behavior of the soil foundation was adopted and adapted furthermore to accommodate the variation of the pore water pressure during the dynamic exciting process. Secondly the parameters of the soil that may be influenced by the variation of the pore water pressure were studied and relationships were further established to simulate the variation of the soil properties in the dynamic state. Finally the responses of the foundations and soil were calculated from the model constructed based on both theoretical theory and empirical data. It is found from the numerical analysis that if the pore water pressure rises at an increasing rate during the late cycles of loading, the responses in displacement could be as much as three times of the case without considering the pore pressure effect. However, if the pore water pressure rises in a decreasing rate at the early loading cycles, the influence of pore pressure on the responses is not that significant.

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THE DYNAMIC MODEL OF SOIL AND FOUNDATION SUBJECTED TO SEISMIC WAVES

As the seismic waves generated by earthquakes and propagating in the soil usually two types of wave are found, namely the body wave and surface wave. Body waves consisting of p-wave (dilatational wave) and s-wave (shear wave) travelling through the interior of the earth, thus the soil and rocks, will be the objects to study in this paper. There are many models being used to simulate the dynamic behavior of foundations and soil subjected to seismic waves (Meek & Veletsos 1974, Veletsos & Wei 1971, Veletsos & Nair 1974, Gazetas & Dobry 1984, Banerjee & Butterfield 1981). The most direct methods are using the equations of elastic waves propagating in the soil to solve for the responses with respect to various position and time. Methods applied include finite element methods, boundary element methods and analytical-numerical combined methods, where the soil foundation is idealized as an elastic half-space with or without layers.

Dynamic Model for Single-layered Soil

A simplified alternative method is to model the soil into a semi-infinite truncated cone, which may model both trnaslational and rotational motions (Meek & Wolf 1992). The soil idealized as a semi-infinite elastic cone with apex height z_0 as shown in Fig.1, where translational cone is for vertical and horizontal motion while rotational cone for rocking and torsion. The wave propagation velocities are $c=c_s$ for the shear wave in horizontal and torsional motion and $c=c_p$ for the dilatational wave in vertical and rocking motion.

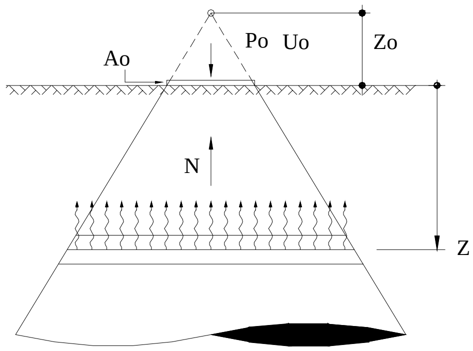

Fig.1 (a) The translational cone model of soil

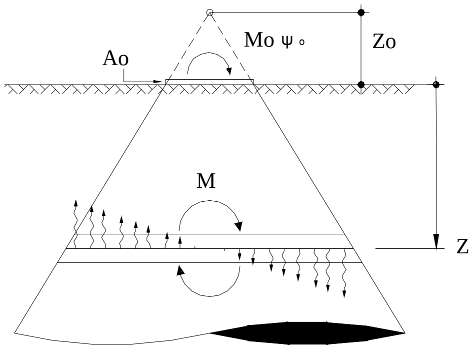

Fig.1 (b) The rotational cone model of soil (after Meek & Wolf 1992)

From the dynamic equilibrium in Fig.1, the gradient of axial force and moment can be found as

$$\frac{\partial N}{\partial z} = \rho A \ddot{u} \tag{1}$$

for translational cone and

$$\frac{\partial M_I}{\partial z} = \rho I \ddot{\varphi} \tag{2}$$

for rotational cone. After substituting the area and the momoent of inertia under variuos depth of the soil-cone such as $A = A_0(z/z_0)^2$ and $I = I_0(z/z_0)^4$ back into the equilibrium and applying the relationships between the force and the displacement gradient such as

$$N = \rho c^2 A \frac{\partial u}{\partial z} \tag{3}$$

and

$$M_I = \rho c^2 I \frac{\partial \phi}{\partial z} \tag{4}$$

the equations of motion become

$$\frac{\partial^2 u}{\partial z^2} + \frac{2}{z}\frac{\partial u}{\partial z} = \frac{\ddot{u}}{c^2} \tag{5}$$

$$\frac{\partial^2 \phi}{\partial z^2} + \frac{4}{z}\frac{\partial \phi}{\partial z} = \frac{\ddot{\phi}}{c^2} \tag{6}$$

As indicated previously, these equations, similar to the famous wave equation except for the second term, can be either solved directly to obtain the displacement or indirectly to relate the imposing sources and responses as a black-box for the equation.

Dynamic Model for Multi-layered Soil

In the single layer soil cone model the propagating energy of earthquakes would not change since there is no reflections between layers but this is not the case for the multi-layered soil model, where traveling waves are to be reflected by rigid soil layers. The motion of the soil of n-th layer under depth z can be presented as

$$u(z,t) = \frac{z_0}{z_0 + z} u_0\left(t - \frac{z}{c}\right) + \sum_{n=1}^{\infty} (-1)^n \left[\frac{z_0 u_0\left(t - \frac{2nd}{c} + \frac{z}{c}\right)}{z_0 + 2nd - z} + \frac{z_0 u_0\left(1 - \frac{2nd}{c} - \frac{z}{c}\right)}{z_0 + 2nd + z} \right] \tag{7}$$

where d is the depth of the soil, n is the layer number and u_0 is the displacement of top layer of soil. Similarly the rotational motion of the n-th layer of soil can be presented as

$$\overline{\varphi}(z,t) = \left(\frac{z_0}{z_0 + z}\right)^2 \varphi_0\left(t - \frac{z}{c}\right) + \left[\left(t - \frac{z}{c}\right)^3 - \left(\frac{z_0}{z_0 + z}\right)^2\right] \cdot f\left(t - \frac{z}{c}\right) \tag{8}$$

It is noted that the last term of the equation is a convolution integral as

$$f(t) = h_1 * \varphi_0 = \int_0^t h_1(t-\tau)\varphi_0(\tau)d\tau \tag{9}$$

where $h_1(t) = (c/z)e^{-ct/z_0}$ and φ_0 is the rotational angle of the top layer of soil.

Solutions for Cone Soil Model

For the single layer model, indirect solutions relating input sources and reponses for the equations of wave propagation can be divided into two forms (Meek & Wolf 1992), namely, the stiffness formulationa and flexibility formulation in terms of the relationship between the input source and reponses on the top layer of the soil.
For the stiffness formulation the responses of force and moment of the foundation due to input displacement, rotation and corresponding velocity are represented as

$$P_0 = Ku_0 + C\dot{u}_0 \tag{10}$$

and

$$M_0 = K_\varphi \varphi_0 + C_\varphi \dot{\varphi}_0 - h_1 * C_\varphi \varphi_0 \tag{11}$$

where

$$K = \rho c^2 A_0 / z_0 \tag{12}$$

$$C = \rho c A_0 \tag{13}$$

$$K_\varphi = 3\rho c^2 I_0 / z_0 \tag{14}$$

$$C_\varphi = \rho c I_0 \tag{15}$$

while

$$h_1(t) = \frac{c}{z} e^{-ct/z_0} \quad \text{for} \quad t \geq 0 \tag{16}$$

$$h_1(t) = 0 \quad \text{for} \quad t < 0 \tag{17}$$

For the flexibility formulation the responses of displacement and rotation of the foundation due to input force, moment and wave velocity are represented as

$$u_0(t) = h_1 * \frac{P_0}{K} = \int_0^t h_1(t-\tau)\frac{P_0(\tau)}{K}d\tau \tag{18}$$

and

$$\varphi_0(t) = h_2 * \frac{M_0}{K_\vartheta} = \int_0^t h_2(t-\tau)\frac{M_0(\tau)}{K_\vartheta}d\tau \tag{19}$$

where

$$h_2(t) = \frac{c}{z_0} e^{-1.5ct/z_0}\left(3\cos\frac{\sqrt{3}}{2}\frac{ct}{z_0} - \sqrt{3}\sin\frac{\sqrt{3}}{2}\frac{ct}{z_0}\right), \quad t \geq 0 \tag{20}$$

and

$$h_2(t) = 0 \quad \text{for} \quad t < 0 \tag{21}$$

It is noticed that the subscript “0” means the responses or input sources on the surface of the soil.

THE INFLUENCE OF PORE WATER PRESSURE TO THE DYNAMIC RESPONSE OF FOUNDATION TO SEISMIC WAVES

The responses of the soil foundation are governed by the input sources and the properties of the soil, which consist of the elastic modulus, shear modulus and Poisson’s ratio. While these properties are related to the velocity of the wave propagation in the soil, the constrained modulus of the soil and all other parameters used in the laboratory to control the experiment, particularly the variation of the pore water pressure. It is important to establish the model for the parameters of soil dynamics in terms of the variation of pore water pressure when the seismic wave induced motion of the soil foundation is required.

Pore Water Pressure Variation in the Earthquake-like Loading

In the evaluation of liquefaction potential for the soil the cycling action of the shear stress is the most important factor, which includes the frequency, amplitude and time duration of the action. This cyclic action results in the rise of the pore water pressure so called the excess pore water pressure that reduces the effective stress of the soil. Once the excess pore water pressure approaches the hydraulic state the effective stress of the soil becomes zero. However, the excitation of the earthquakes is cyclic without regular amplitude, frequency or duration while most tests performed in the laboratory are subjected to regular cyclic loadings. Therefore, it is more difficult to establish the model accounting for irregular behavior based on regular experimental data.

To relate the pore pressure ratio, the ratio between the pore water pressure and the constrained stress, Lee and Albaisa (1974) and DeAlba et al. (1975) suggested a formula that pore pressure is presented in terms of the number of loading cycles and soil properties as

$$r_u = \frac{1}{2} + \frac{1}{\pi}\sin^{-1}\left(2r_N^{\ 1/\alpha} - 1\right) \tag{22}$$

where r_u is the pore pressure ratio, r_N is the ratio of number of the loading cycles to the number of cycles that results in the initial liquefaction, α is the parameter related to the soil properties and test conditions. According to this formula the excess pore pressure generated from the cyclic loading can be estimated before liquefaction status is reached as shown in Fig.2, where α =0.7 represented an average rising rate of pore pressure corresponding to the number of loading cycles.

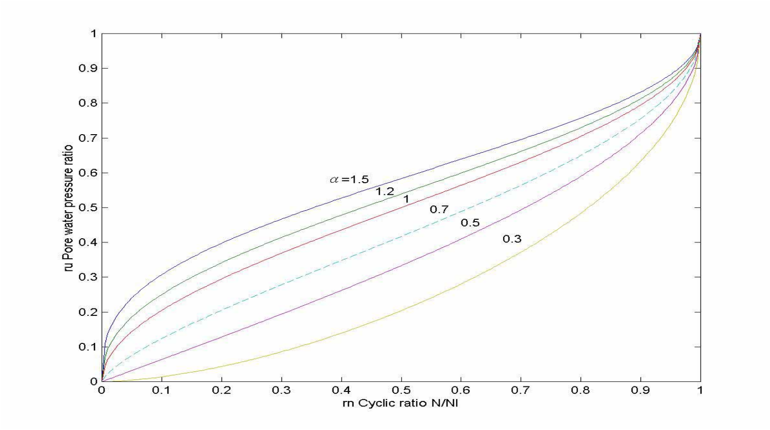

Fig.2 The relationship between pore pressure ratio and ratio of cyclic loading numbers (after DeAlba et al. 1975)

Now the question is how many cycles will be needed for the initiation of liquefaction and how to relate the results of regular cyclic loading test to the earthquake generated cyclic loading state. The number of loading cycles required for initial liquefaction will largely depend on the cyclic loading and constrained stress. A simple formulation was provided by Seed and et al. (1976) for the number of so called equivalent uniform stress cycles related to earthquakes of different magnitudes. Based on the formulation at an amplitude of 65% of the peak stress, the number of loading cycles can be related to the magnitude of various earthquakes. For the 921 Chi-Chi earthquake of magnitude of 7.3 in Richter's scale the number of equivalent stress loading cycles is about 10. Therefore, the test data from Lee and Albaisa (1974) was adopted for the simulation of pore water pressure generated from the earthquake-like loading, which is presented in Fig.3, where the line is the simulated curve and little circles are the test data.

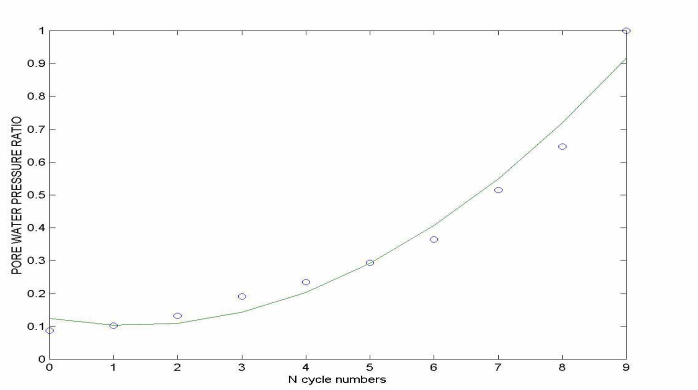

Fig.3 The variation of pore water pressure related to number of loading cycles for equivalent stress

Pore Water Pressure on the Seismic Wave Propagation

Many parameters of the soil are related to the velocity of the seismic waves propagating in the soil such as the most basic properties of soil: elastic modulus, shear modulus and Poisson's ratio, presented as

$$M = \rho c_p^2 \tag{23}$$

$$G = \rho c_s^2 \tag{24}$$

$$\nu = \frac{(r_v)^2 - 2}{2(r_v)^2 - 2} \tag{25}$$

where $r_v = c_p / c_s$ is the ratio of propagating velocity of dilatation and shear waves.

For the dynamic model of soil foundation adopted in this study many parameters are also related to either the velocity of wave propagation or the propagation ratio r_v, namely, the aspect ratio z_0 / r_0, the dimensionless parameter cdt / z_0 and temporal parameter $T / 2c$.

Unfortunately, there is no explicit formulation that may relate the propagation velocity of the seismic waves to the variation of pore water pressure. However, the pore water pressure does influence the basic property of the soil such as the constrained modulus of the soil M that may be related to the variation of the pore water pressure Δu_c as indicated in the research of Boit (1956).

$$M = \alpha' M_w \frac{\sigma_3}{\Delta u_c} - \alpha'^2 M_w \tag{26}$$

where M_w is the bulk modulus of water, α' the parameter presenting the degree of the compactness for the soil, which is between the void ratio of the continuum and the unit value, and σ_3 the constrained stress. According to this formula the variation of the constrained modulus of soil corresponding to pore pressure ratio can be shown as Fig.4

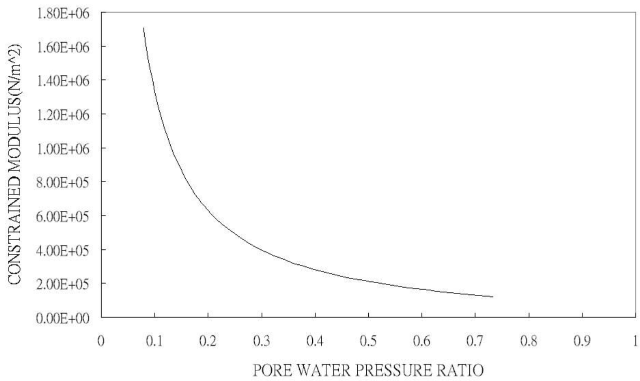

Fig.4 Constrained modulus related to variation of pore water pressure

When the shear modulus is assumed to be constant both the propagation ratio and Poisson's ratio can be obtained directly, thus the parameters that required in the calculation for the soil-foundation model can also be related to the variation of the pore water pressure.

NUMERICAL RESULTS AND DISCUSSION

In the numerical analysis the influence of the variation of pore water pressure on the foundation responses was taken into accounts. The multi-layer model was applied for the analysis and two types of loading were applied, namely the regular harmonic loading and the earthquake-like loading, which is similar to 921 Chi-Chi earthquake.

Effect of Pore Water Pressure due to Harmonic Loadings

For the soil foundation subjected to multi-cycle loadings the harmonic loading with constant amplitude was applied. The influence of variation of pore water pressure was taken into account for all parameters related. As shown in Fig.5 and Fig.6 are the comparison of the responses of displacement and rotation of the foundation subjected to harmonic cyclic loading respectively, where the input frequency of the harmonic loading is 1 Hz.

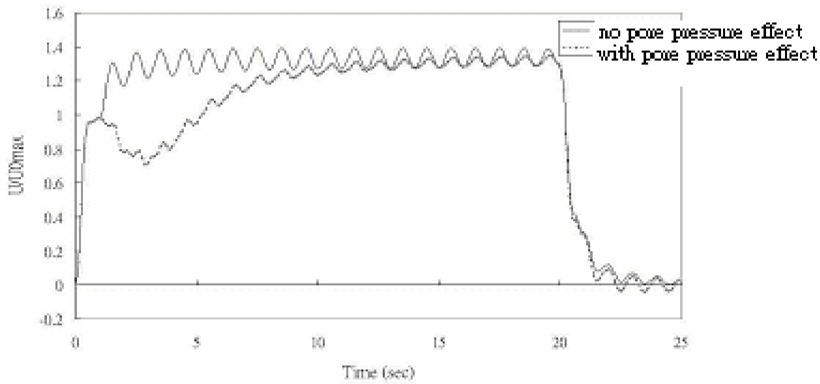

Fig.5 The comparison of the displacement response w/t the pore pressure effect (harmonic loading)

It can be seen that for the displacement response without considering pore water pressure the response goes up directly to a constant level and then vibrates along that constant level. With consideration of the pore pressure variation, the response has a larger fluctuation in the early loading stage. However, it almost matches with the one without consideration of pore pressure variation during the late loading stage.

For the rotational responses the vibration modes between these two cases are almost the same except that the soil with accounting for the pore pressure effect vibrates at a higher level of line.

Effect of Pore Water Pressure due to Earthquake Loadings

The effect of variation of pore water pressure on the responses of foundation was evaluated when the soil subjected to earthquake-like loadings. In the analysis the time history of acceleration and velocity of 921 Chi-Chi earthquake recorded at TCU70 station was adopted. Fig.7 Shows the comparison of the displacement response with or without taking the pore pressure effect into account, where the parameter $\alpha = 1.5$ means that the pore pressure rises quickly in the early loading stage and then goes mildly in the late loading cycles. It is observed that except for little shifting of the curve two responses are not differed significantly in terms of the amplitude and the fluctuations.

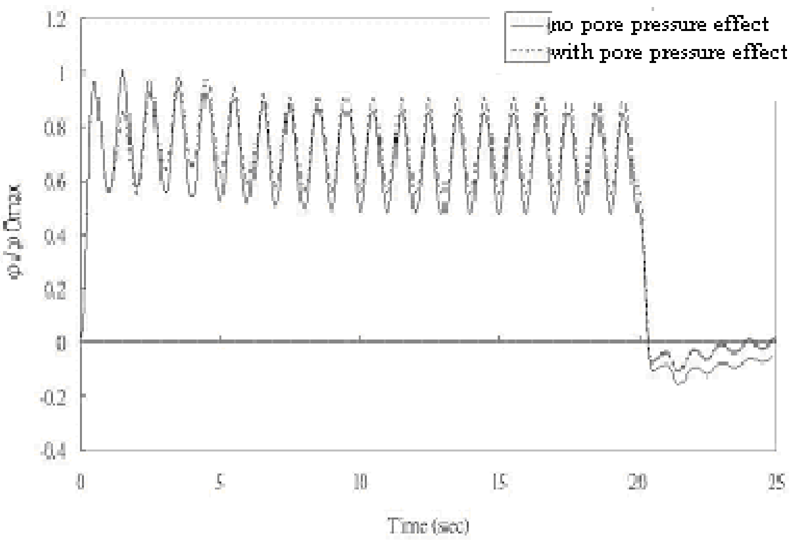

Fig.6 The comparison of the rotational response w/t the pore pressure effect (harmonic loading)

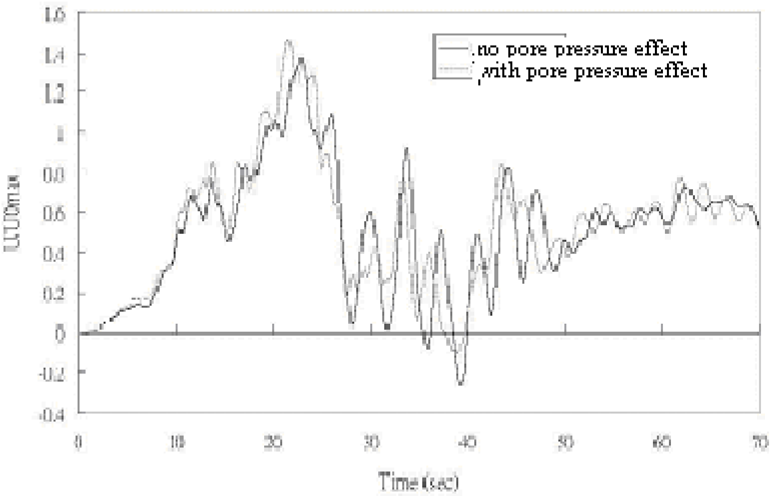

Fig.7 The comparison of the displacement response w/t the pore pressure effect (earthquake loading, $\alpha = 1.5$)

Fig.8 also shows the comparison of the displacement response with or without taking the pore pressure effect into account, where the parameter $\alpha = 0.7$ the average value for the curve (as Fig.2). It was found that with accounting for the pore water pressure variation the displacement response became larger and also had larger fluctuations.

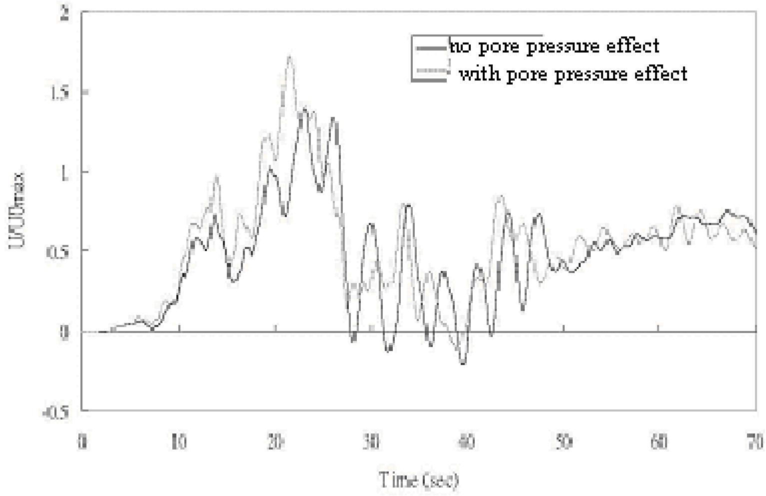

Fig.8 The comparison of the displacement response w/t the pore pressure effect (earthquake loading, $\alpha = 0.7$)

Fig.9 is the comparison of the displacement response with or without taking the pore pressure effect into account, where the parameter $\alpha = 0.3$ the smallest value for the curve indicating that the pore pressure rises at an increasing rate during the late cycles of loading. It was found that with accounting for the pore pressure variation the displacement response became significantly larger, particularly around 30 seconds of loading, at which the response is about three times of that without considering the pore pressure effect.

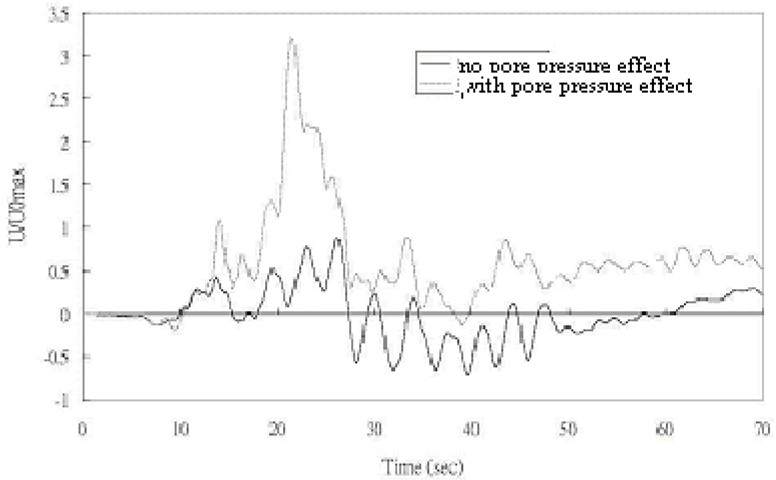

Fig.9 The comparison of the displacement response w/wt the pore pressure effect (earthquake loading, $\alpha = 0.3$)

CONCLUSIONS

In this study the influence of variation of pore water pressure on the dynamic response of foundation was studied. A simplified dynamic model of semi-infinite cone-like for the soil-foundation response subjected to dynamic loading was adopted and adapted with accounting for the pore pressure effect. The variation of pore water pressure was furthermore related to the propagation velocity of seismic waves in the soil, which also affected the properties of the soil and parameters utilized in the analytical model.
In the numerical analysis dynamic loadings applied include the regular harmonic loading and earthquake-like loadings. According to the results of numerical analysis for both with and without accounting for the pore water pressure, it was found that for the harmonic loadings there is difference for the behavior of displacement response for the foundation. The foundation with consideration of pore water pressure has larger fluctuation in the displacement and higher amplitude in rotation responses.
For the earthquake input analysis, three types of variation for the pore water pressure corresponding to the cycle numbers of shear loading were considered in terms of the parameter α. It was found that for smaller number of α, indicating that the pore pressure rises at an increasing rate during the late cycles of loading, the responses in displacement could be as much as three times of the case without considering the pore pressure effect. However, if the pore water pressure rises in the early loading cycles, the influence on the responses is not that significant.

ACKNOLEGEMENT

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