Numerical Analyses of Dynamic Responses of an Earth Dam during 1999 Chi-Chi Earthquake in Taiwan

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ABSTRACT: The Pastor and Zienkiewicz (P-Z) model was adopted here as the constitutive model to study the dynamic responses of the Liyutan dam subjected to the Chi-Chi earthquake. For numerical simulation, the shell materials of the earth dam are assumed to satisfy the P-Z model. The optimal material parameters of P-Z model were judged according to the experimental results by Center Region Water Resource Office in Taiwan. Staged construction, seepage, static equilibrium and dynamic response are sequentially analyzed. A comparison is performed between the P-Z model and Mohr-Coulomb model through the dynamic analysis of the Liyutan dam under Chi-Chi earthquake. The influence of permeability of shell on the generation of pore water pressure under earthquake loading was studied. The results show that the large horizontal permanent movements at the upstream shell were resulted and the larger vertical settlement took place at the top of dam after the earthquake. The Mohr-Coulomb model results in higher pore water pressure compared to those obtained of the P-Z model during the earthquake shaking. The pore pressure parameter in upstream shell slightly decreases with the increase of the permeability of shell.

INTRODUCTION

The Liyutan Dam, located in Miaoli, Taiwan, is a roller compacted earth dam with 96 m high and 235 m long. The stage construction of the dam was simulated numerically using a two dimensional finite difference program, FLAC 5.0. A typical configuration and finite difference mesh for the Liyutan dam was generated as shown in Fig. 1. The dam is assumed to be situated above a hard rock formation. Therefore, the base of the dam is assumed to be impermeable and fixed, i.e. the deformability is constrained and sliding will be prevented at the base. The dam materials were added up sequentially to the top of the dam by 20 different layers in the numerical simulation. Seepage analysis was performed considering a 60 m water level which was the water level when the Chi-Chi earthquake (M_L=7.3) occurred. The initial effective stress of the dam was obtained after the seepage analysis and static equilibrium has reached before applying acceleration caused by the earthquake. The acceleration time history during the Chi-Chi earthquake is used as the input to the base of the dam for the dynamic analyses in order to estimate the dynamic response of the dam under strong earthquake. The dynamic response of Liyutan Dam under Chi-Chi earthquake loading was studied by Feng et al. (2010). However, the pore water pressure of dam after the earthquake has not yet been fully investigated. In this paper, the numerical results of displacement time history and the pore water pressure time history of the Liyutan Dam under Chi-Chi earthquake loading were computed.

The P-Z model was first developed by Pastor et al. (1990) to predict the soil response such as accumulation of plastic strain and excess pore water pressure generated during dynamic loading. In this model, it can be considered that the progressive decay in the soil stiffness with increasing pore water pressure, accumulation of plastic strain, stress-dilatancy and hysteretic loops for energy dissipation. The main considerations for selecting the P-Z model were that the model has a good capability of representing the mechanical behavior of both dense and loose sands under dynamic loading. Therefore, this study applied this model for simulation of the dynamic response of Liyutan dam under Chi-Chi earthquake loading. In order to estimate the performance differences of the P-Z model and other constitutive model in simulating the dynamic response of the dam, Mohr-Coulomb model was utilized. Moreover, the pore water pressure time history under various permeability of the shell was estimated in order to study the influence of permeability of the shell on pore water generation in the dam during the earthquake.

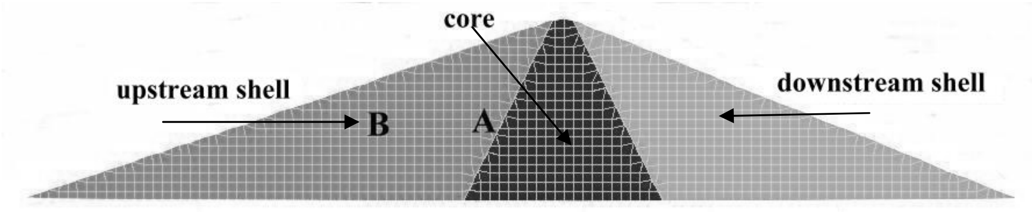


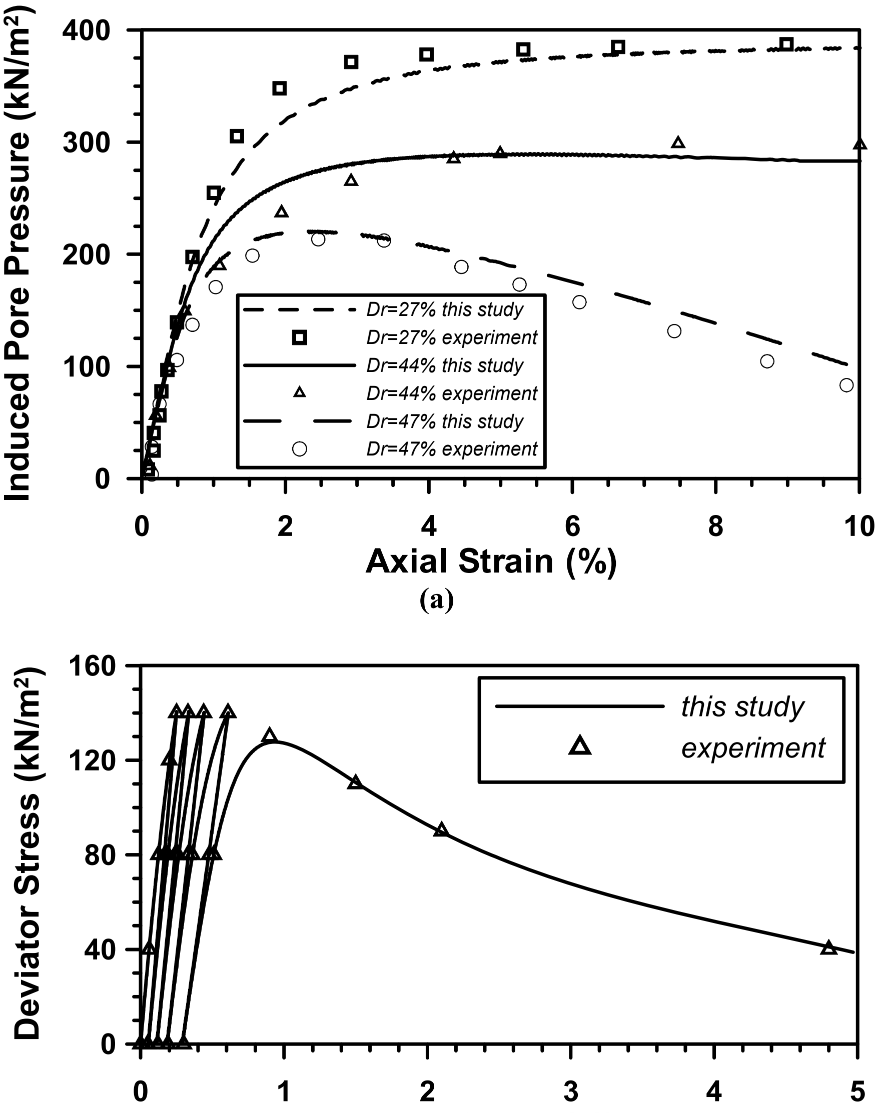
FIG. 1. A typical finite difference mesh of the Liyutan dam in FLAC.

NUMERICAL MODEL

Verification of Computational Algorithm Based on the P-Z Model

The formulations of the P-Z model were shown in Pastor et al. (1990) in details. A FISH subroutine was developed based on the P-Z model in this study. Two numerical analyses of triaxial tests were simulated for verifying the performance of the model.

CU tests on Banding Sands under three relative densities were used for evaluation first. In addition, a numerical simulation of the behavior of sand under cyclic loading without extension was performed. These simulated results were compared with the experimental results of Castro (1969). It can be observed that the simulated results of this study are close to those of Castro as indicated in Fig. 2. Therefore, the accuracy and the performance of the developed FISH subroutine based on the P-Z model in this study are satisfied.



(a)

(b)

FIG. 2. Comparison between simulated and experimental results for (a) undrained triaxial test and (b) cyclic undrained triaxial test.

Material Characteristics of the Liyutan Dam

The material properties of the dam were divided into the shells and core. The shells and core of dam are made of cohesionless and clayey soils, respectively. It could result in liquefaction as the pore water pressure building up in the saturated cohesionless soils. In the numerical analyses, the shells and core of the dam are assumed to be satisfied to the P-Z sand model and Mohr-Coulomb model, respectively. The material parameters were found by using regression method with the triaxial compression test results from Central Region Water Resources Office in Taiwan (1991). The material parameters used in the simulations for the typical core are as follows: shear modulus G=579MPa, bulk modulus K=5,500MPa, unit mass ρ=2,100kg/m^3, cohesion c=83.5kPa, friction angle ϕ=27°, permeability coefficient $k=1\times10^{-7}\ \mathrm{cm/sec}$. The material parameters of the P-Z model for the shell are as follows: K_0=140MPa, G_0=190MPa, M_g=1.4, M_f=0.6, $\alpha_g=\alpha_f$=0.45, β_0=2.5, β_1=0.02, H_0=25,000, and $\gamma=\gamma_1$=1.

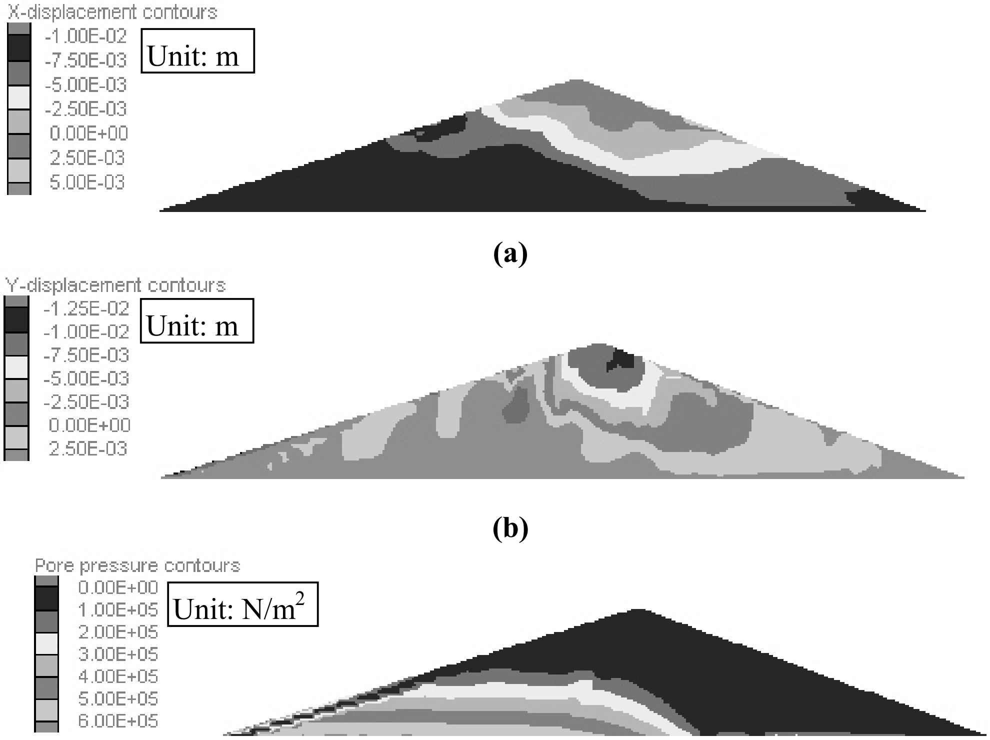
Simulation Procedures

The dam is formed by simulating staged construction using 20 finite difference grid layers. The purpose of the construction simulation is to obtain a reasonable stress state for the dam during the construction phase before applying retaining water behind the dam. Thus, when a grid layer is placed, a new static equilibrium for the dam is carried out. The steady state seepage calculation is performed after the completion of the staged construction. Steady state seepage of the dam for a 60 m water level is then performed without interaction with mechanical equilibrium. The final state of static equilibrium, called initial stress state, of the dam was then computed again after the steady state seepage has reached. By using the same grid and the obtained initial stresses, the acceleration time history recorded during the Chi-Chi earthquake is applied to the base of the dam. The acceleration time histories are filtered under 5 Hz to reduce the chance of numerical instability before applying. In addition, baseline corrections for the acceleration time histories are also made for zero velocity and displacement after integration. To save time of calculation, the duration used for simulation is only considered from 16sec to 32sec of the acceleration time history. The energy of this duration is about 90% of the total energy of Chi-Chi earthquake, which is judged from the Husid plot.

RESULTS OF THE NUMERICAL ANALYSES

Dynamic Responses of the Liyutan Dam with the P-Z Model

The calculated horizontal and vertical permanent displacements and the pore water pressure from the numerical analysis of the Liyutan Dam under the Chi-Chi earthquake loading are shown in Fig. 3. The computed maximum horizontal permanent displacement of 1.25cm occurred at the upstream shell and maximum settlement of 1.25cm occurred at the top of dam. Since pore water pressure built up in upstream shell during earthquake simulation, thus large horizontal movements at the upstream shell were resulted. Also, larger settlement took place at the top of dam. Generally, the dam moved toward upstream permanently after the earthquake.



(a)

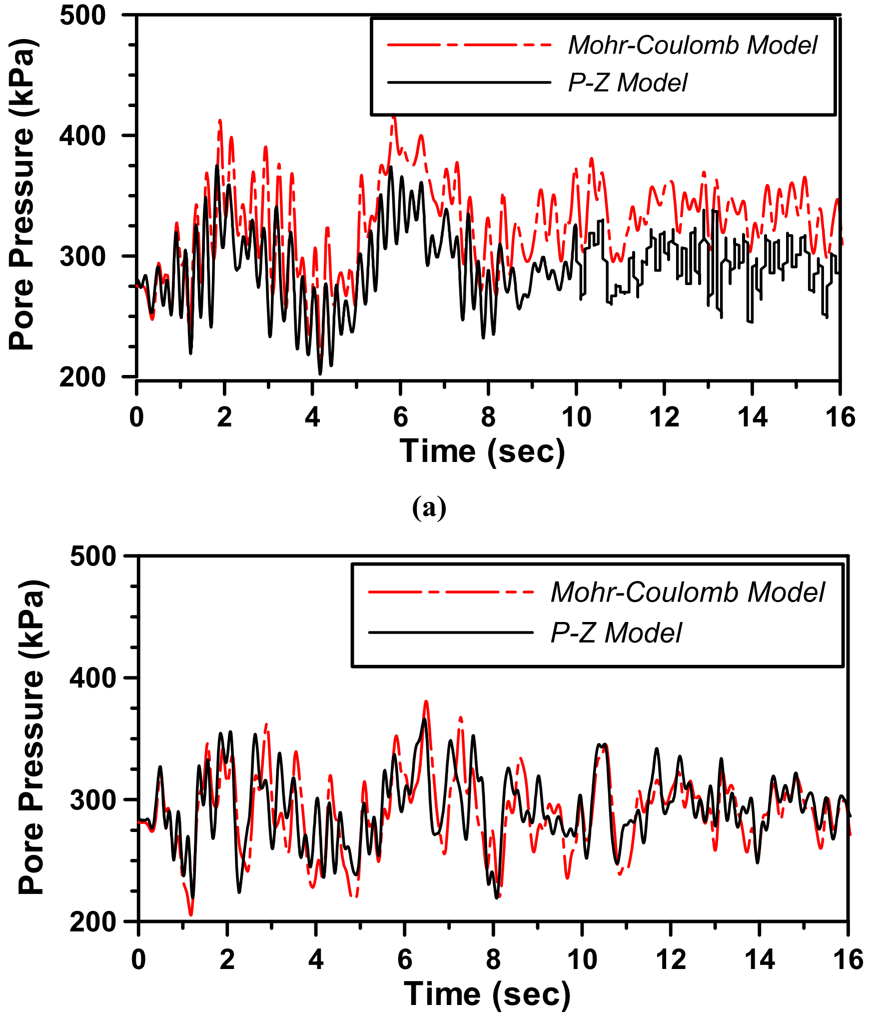
(b)

(c)

FIG. 3. Contours at the end of the Chi-Chi earthquake with the P-Z model : (a)horizontal permanent displacement (b) vertical permanent settlement and (c) pore water pressure.

Influence of Plasticity Based Model on Pore Water Pressure Generation

In order to study the influence of plastic model on excess pore water pressure of the dam generated during earthquake, the Mohr-Coulomb model was also used. The simulated results using the P-Z model and those obtained of Mohr-Coulomb model are compared in Fig. 4. The material properties of the shell using Mohr-Coulomb model are as follows: shear modulus G=403MPa, bulk modulus K=1,125MPa, unit mass ρ=2,100kg/m^3, cohesion c=14.5kPa, friction angle ϕ=41°, permeability coefficient $k = 5\times10^{-6}$ cm/sec for upstream shell; shear modulus G=400MPa, bulk modulus K=867MPa, unit mass ρ=2,200kg/m^3, cohesion c=30.5kPa, friction angle ϕ=35°, permeability coefficient $k = 5\times10^{-6}$ cm/sec for downstream shell. Fig. 4 shows the time history of pore water pressure at two nodes (A and B in Fig.1) located in upstream shell. As can be seen in Fig. 4, the Mohr-Coulomb model results in higher pore water pressure compared to those obtained of the P-Z model. The results also demonstrate that the pore water pressure at Node A is higher than that at Node B. The reason could be Node B is close to the upstream slope than Node A, so that pore water pressure at Node B dissipated faster than Node A.



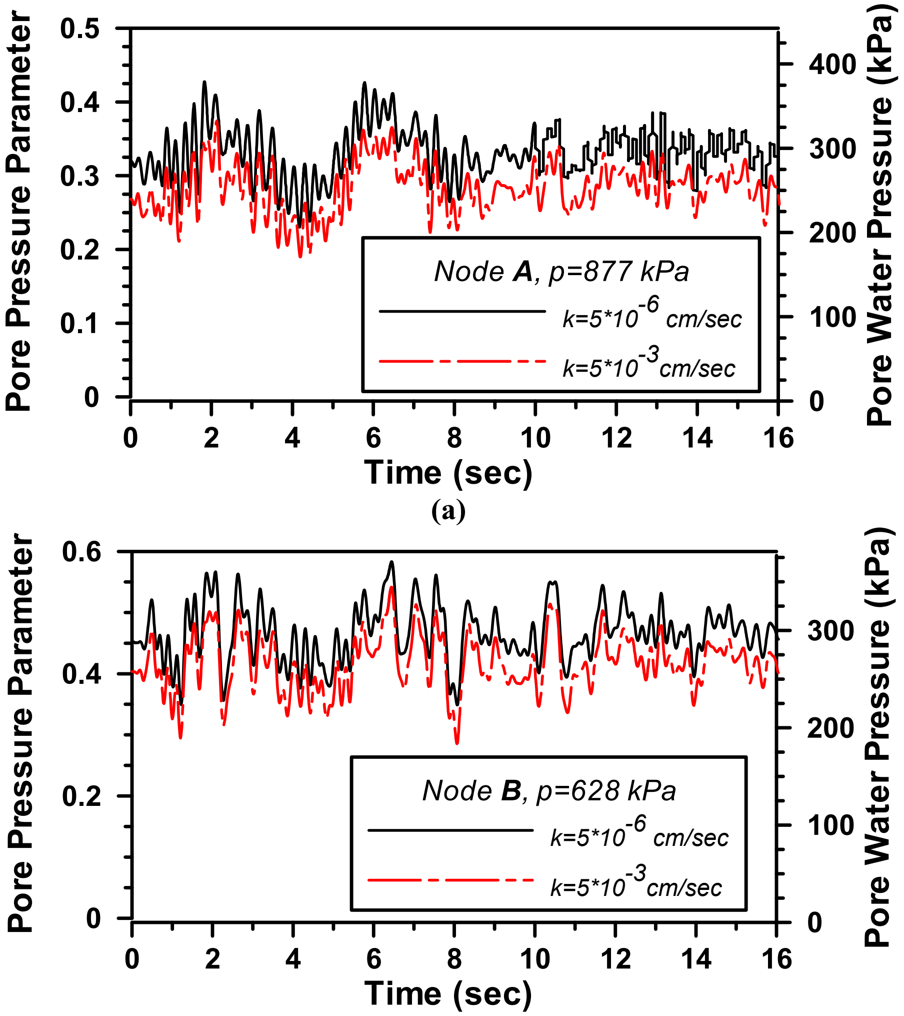
(a)

(b)

FIG. 4. The time history of pore water pressure using the P-Z model and Mohr-Coulomb model: (a)Node A (b)Node B.

Influence of Permeability on Pore Water Pressure Generation

To study the influence of permeability of the shell on pore water pressure induced in upstream shell during earthquake, an additional permeability coefficient of shell



(a)

(b)

FIG. 5. The time history of pore water pressure with different permeability of the shell: (a)Node A (b)Node B.

was estimated, k= 5×10^{-3}cm/sec. This permeability is close to that of gravely sand. We define the pore pressure parameter as the current pore water pressure divided by the mean stress, p, during initial stress state of the element. The time histories of pore water pressure and pore pressure parameter at Node A and Node B during the earthquake are shown in Fig. 5. It can be seen from Fig. 5 that all of the pore pressure parameters are lower than unity, that is, there is no liquefaction having occurred at Node A and B during the earthquake. The location of Node B is closer to upstream slope than Node A; therefore, the mean stress at Node B is less than that at Node A. The pore pressure parameters at Node B are larger than that at Node A because the mean stress at Node B is smaller. Therefore, the liquefaction potential at Node B is higher than that at Node A.

The results also indicate that the pore pressure parameters in gravely sand ($k=5\times10^{-3}$ cm/sec) are slightly lower than those of silty sand ($k=5\times10^{-6}$ cm/sec). Accordingly, to reduce liquefaction potential, it is beneficial that we use a higher permeable soil as the shell material.

CONCLUSIONS

Based on the numerical analyses presented, the following conclusions can be made:

1. The large horizontal permanent movements at the upstream shell were resulted and the larger vertical settlement took place at the top of dam after Chi-Chi earthquake.
2. Using Mohr-Coulomb model results in higher pore water pressure than those obtained from using the P-Z model during the earthquake shaking.
3. The pore pressure parameters near the surface of the upstream shell will be higher than those of other locations due to the lower mean stress near surface. Therefore, the liquefaction potential near upstream slope is higher.
4. The liquefaction potential in gravely sand ($k=5\times10^{-3}$cm/sec) are slightly lower than those of silty sand ($k=5\times10^{-6}$ cm/sec) during earthquake shaking.

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