Effects of Core on Dynamic Responses of Earth Dam

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ABSTRACT: This paper investigates the dynamic response of the Pao-Shan II Dam subjected to the Chi-Chi earthquake (\(M_L=7.3\)) in Taiwan by using FLAC\(^{3D}\). The elastic modulus of the dam is considered to vary with mean stress in this study. Staged construction, seepage, static equilibrium and dynamic response are sequentially analyzed. Fourier power spectra are analyzed as the earth dams subjected to a sweep frequency dynamic loading. Influences of core dimensions on the dynamic responses of the earth dam are investigated. The influence of the core width-height ratio and length-height ratio of the dam on the first natural frequency is studied in this study. The results show that 3D effect could be neglected for \(\eta > 4\) cases. The first natural frequency decreases with the increase of core width-height ratio or length-height ratio of an earth dam. The first natural frequency increases slightly after the seepage phase. The stiffness of the dam decreases at the end of an earthquake which causes the first natural frequency to decrease.

1. INTRODUCTION

The Pao-Shan II Dam, located in Hsinchu, Taiwan, is a roller compacted earth dam with 61 m high and 360 m long. The stage construction of the dam was simulated numerically using a three dimensional finite difference program, FLAC\(^{3D}\). The dam materials were added up sequentially to the top of the dam by 10 different layers. Seepage analysis was performed considering a 56 m water level. 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. Since the Pao-Shan II Dam did not undergo any strong earthquake, the acceleration time history during the Chi-Chi earthquake is used as an input to the base of the dam for the dynamic analyses in order to estimate its dynamic response under strong earthquake. The
numerical results of displacement time history were computed at the dam. In order to estimate the first natural frequency of vibration for the earth dam, 5 length-height ratios and 4 core width-height ratios are assumed, and a proposed procedure to find natural frequency is performed in this study. Moreover, they were estimated in construction, full water level, and the Chi-Chi earthquake phases in order to find out the variation of natural frequency on these phases.

2. NUMERICAL MODEL FOR THE STUDY

2.1 Earth Dam Configuration

A typical configuration and finite difference mesh for the dam was generated and discretized by FLAC3D, as shown in Fig. 1. The dam with height H, length L and core width W 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. In addition, the crests are placed at both sides of the core and the filter is presented between the core and below the downstream crest. The Pao-Shan II Dam with length L=360 m, height H=61 m, width of 352 m, and core width W=55 m was assumed for dynamic analysis. Since there are mountains located at both sides of the dam, the side boundaries are assumed to be fixed and impermeable at the both ends of the dam in z direction. Length of the dam is normalized with respect to height, thus, a length-height ratio $\eta$ is used to estimate the 3D effect on dynamic response. In the same way, a core width-height ratio $\lambda$, i.e. core width W divides by dam height H, is used to estimate the influence of core width on natural frequency of an earth dam. In order to estimate the impacts of dimensions on natural frequency of an earth dam, a fixed dam width of 352 m and height of 61 m are used, five different length-height ratios ($\eta=2$, 3, 4, 5 and 6) and four core width-height ratios ($\lambda=0.4$, 0.6, 0.9 and 1.2) are used for analyses.

![FIG. 1. A typical finite difference mesh of an earth dam by FLAC](image)

2.2 Material Characteristics of the Earth Dam

For the numerical analysis, the crest and core of the earth dam are assumed to be satisfied to the Mohr-Coulomb model. The material properties of the dam were divided into the crest, core and filter. Material properties of the dam are estimated
from the field and laboratory testing results during construction. The engineering properties for the simulation are listed in Table 1. Because the dam is huge, the stiffness could be different in any location. Therefore, the soil modulus will be considered to vary with the mean stress as

\[ E = KP_a \left( \frac{P}{P_a} \right)^n \]

where \( K \) is the modulus constant, \( n \) is the modulus exponent and \( P_a \) is the atmospheric pressure. The material parameters, \( K \) and \( n \), for the core and crest were found by using regression method with the triaxial compression test results by Central Region Water Resources Office in Taiwan. The parameters \( K=592 \) and \( n=0.3 \) for the crest are used, while \( K=888 \) and \( n=0.1 \) for the core. A FISH program is coded and used by FLAC\(^{3D}\) in order to perform the function of Eq. 1.

### Table 1. The material parameters of the earth dam  
(Central Region Water Resources Office, 2006)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Density ( \rho ) (kg/m(^3))</th>
<th>Young’s Modulus E (MPa)</th>
<th>Poisson ratio ( v )</th>
<th>Cohesion ( c' ) (kPa)</th>
<th>Friction angle ( \phi' ) (°)</th>
<th>Permeability, ( K_p ), (m/ sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest</td>
<td>2090</td>
<td>46</td>
<td>0.355</td>
<td>19</td>
<td>33.8</td>
<td>2.2 \times 10^{-7}</td>
</tr>
<tr>
<td>Core</td>
<td>2120</td>
<td>15.5</td>
<td>0.36</td>
<td>-</td>
<td>31.3</td>
<td>8.5 \times 10^{-8}</td>
</tr>
<tr>
<td>Filter</td>
<td>2110</td>
<td>31</td>
<td>0.412</td>
<td>-</td>
<td>36</td>
<td>3.2 \times 10^{-4}</td>
</tr>
</tbody>
</table>

2.3 Procedures of the Simulation

The dam is formed by simulation of stage construction using 10 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 layer is added, a new static equilibrium for the dam is carried out. The steady state seepage calculation is performed after completion of the dam construction without interaction with mechanical equilibrium. Uncoupled with mechanical analysis, steady state seepage of the dam for a 56 m water level is then performed. 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 to the base. In addition, baseline corrections for the acceleration time histories are also made for zero velocity and displacement after integration.

In order to find the natural frequency of a dam, a harmonic acceleration with multiple frequencies is inputted to the base of the dam. From Fourier spectrum analysis, the natural frequency of a dam can be obtained as its response is amplified, i.e., resonant occurs. If the source is a harmonic loading with multiple exciting
frequencies, it should be possessed the same amplitude in all forced vibration frequencies, that is the same energy in all exciting frequencies is fair subjected. Therefore, it could be rational as the vibration source with the same acceleration amplitude in all exciting frequencies. Because the first natural frequency is smaller than 10 Hz from the past research, the harmonic exciting frequency will be varied from 0.01 Hz to 10 Hz for the natural frequency analysis. The exciting acceleration of multiple frequencies can be expressed as the following:

\[ a(t) = \sum_{i=1}^{1000} 10^{-6} \sin\left(\frac{\pi t}{50}\right) \]  

in which \( t \) is time, and the acceleration amplitude is limited to a small value of \( 10^{-6} \) to assure it is in elastic range. It is found that the stress field inside a dam and the following analyses are not influenced according to the acceleration level. A FISH program is also coded in FLAC in order to apply a multiple frequencies (0.01~10 Hz) harmonic acceleration to the base of the dam.

3. RESULTS OF THE NUMERICAL ANALYSIS

3.1 Dynamic Responses of the Pao-Shan II Dam

The calculated stress of \( \sigma_{xx} \) and \( \sigma_{yy} \) from the numerical analysis after the Chi-Chi earthquake are shown in Fig. 2, respectively. The computed maximum stress \( \sigma_{xx} \) and \( \sigma_{yy} \) occur at the center of the dam base.

![Stress contours from the dynamic analysis](image)

**FIG. 2.** Stress contours from the dynamic analysis : (a) \( \sigma_{xx} \), and (b) \( \sigma_{yy} \)

3.2 Parametric Analysis on Natural Frequency

3.2.1 Influence of Length-Height Ratio of a Dam on the Natural Frequency

In order to study the influence of length-height ratio, length in \( z \) or axial direction divided by dam height, on natural frequency of an earth dam, the width-height ratio of the core will be fixed at \( \lambda=0.9 \). The impacts of length-height ratios of 2, 3, 4, 5 and 6 on the first natural frequency are studied, and the results can be observed from Fig.
3. As can be seen in Fig. 3, the first natural frequency of an earth dam decreases with increasing length-height ratio. The increase of the axial length of a dam may cause the dam to behave more flexible and to have lower natural frequency. The length-height ratio has less influence on natural frequency as $\eta > 4$. The first natural frequency is about 2.5 Hz as $\eta > 4$. For $\eta > 4$ cases, the result from 3D analysis is the same as that from plane strain case. Thus, the 3D effect could be neglected for $\eta > 4$ cases.

![Graph](image1)

**FIG. 3.** The first natural frequency verse length-height ratio

### 3.2.2 Influence of Core Width-Height Ratio on Natural Frequency

To study the influence of core dimensions on the natural frequency of a dam, the length-height ratio, $\eta$, is assumed to be fixed at 6, and core width-height ratio, $\lambda$, is equal to 0.4, 0.6, 0.9 and 1.2. It can be seen from Fig. 4 that the natural frequency decreases with the increase of core width-height ratio. Since the core of a dam is made of soft materials like clay, a dam will become more flexible as the core width-height ratio increases. Thus, the first natural frequency decreases as the core width-height ratio increases. The results also indicate that the first natural frequency is close to 2.5 Hz for $\lambda > 0.9$ cases.

![Graph](image2)

**FIG. 4.** The first natural frequency verse core width-height ratio
3.2.3 Influence of Phases on Natural Frequency

In order to study the influence of each phase, i.e. construction, seepage, and Chi-Chi earthquake phases, on natural frequency of a dam, the dimension of the earth dam will be fixed at $\eta=6$ and $\lambda=0.4$, the same dimension as the Pao-Shan II dam. In addition, a predominant frequency during the Chi-Chi earthquake is also estimated. The predominant frequency is 0.83 Hz in the Chi-Chi earthquake. The numerical results showed that the first natural frequency after stage construction, after seepage and after earthquake is 3.38 Hz, 3.58 Hz and 1.59 Hz, respectively. The first natural frequency of a dam increases after the seepage phase. The reason could be the water weight is placed on the upstream surface of the dam and to result in increasing stresses in the dam. The dam may then become stiffer, and the natural frequency is larger. However, for the phase during earthquake condition, the pore water pressure increases and effective stress decreases due to earthquake load. The stiffness of the dam decreases at the end of the earthquake. Therefore, the first natural frequency decreases at the end of the earthquake.

4. CONCLUSIONS

Based on the numerical analyses presented in this paper, the following conclusions may be made:

1. The 3D effect could be neglected for $\eta > 4$ cases. The first natural frequency is close to 2.5 Hz as $\eta > 4$.
2. The first natural frequency decreases with the increase of the core width-height ratio or length-height ratio of an earth dam.
3. The first natural frequency increases slightly after the seepage phase.
4. The first natural frequency decreases at the end of an earthquake due to the decrease of stiffness of the dam.

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REFERENCES

