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# Dynamic response of Li-yu-tan earthdam subjected to the 1999 Chi-Chi earthquake in Taiwan

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ABSTRACT: The dynamic response of the Li-yu-tan earthdam subjected to the 1999 Chi-Chi earthquake (ML = 7.3) in Taiwan was analyzed using *FLAC* Ver. 5.0 (Itasca 2005). Staged construction, seepage, static equilibrium and dynamic response were sequentially analyzed. The 921 recorded acceleration time histories were input to the base of the dam for 45 seconds. The *FLAC* built-in "Sigmoidal 4" equivalent-linear model and Mohr-Coulomb soil model were adopted with Rayleigh damping assignment. Numerical results of the analysis are close to the acceleration/displacement time histories monitored at the top of the dam. Influences of water levels on the dynamic responses of the dam were investigated for full water level (90 m) and low water level (30 m).

## 1 INTRODUCTION

This study used *FLAC* Ver. 5.0 (Itasca 2005) to analyze the dynamic response of Li-yu-tan dam subjected to the 1999 Chi-Chi earthquake (ML = 7.3) in central Taiwan. The dam is a roller compacted earthdam which is 96 m high and 235 m long. It is an off-channel reservoir. The construction stage of the dam was numerically simulated by 20 layers of the dam materials added sequentially up to the top of the dam. Seepage analysis was performed using a 60-meter water level, which was the water level while the earthquake struck. After the seepage analysis, the initial stress state of the dam (before applying the earthquake acceleration) was obtained by computation of static equilibrium. The horizontal and vertical peak ground accelerations monitored at the base of the dam site are 0.149 g and 0.108 g, respectively. Because the vertical shaking of Chi-Chi earthquake is notable, both the horizontal and vertical monitored acceleration time histories were input to the base of the dam for 45 seconds in the dynamic analyses. The accelerations were filtered under 5 Hz before input. The *FLAC* built-in "Sigmoidal 4" equivalent-linear hysteretic model and Mohr-Coulomb soil model were simultaneously adopted with Rayleigh damping assignment. The numerical results of acceleration time history and Fourier spectra were compared with monitored data at the top of the dam. Permanent displacements at the top, upstream and downstream shells were also evaluated. The comparisons are satisfied with reasonable ranges of differences. Analyses of full water level (90 m) and low water level (30 m) were performed to predict the dynamic responses of the dam at these water levels. Comparisons were made to observe the differences in dynamic responses among the three different water levels.

## 2 NUMERICAL MODEL

To achieve the two-dimensional dynamic response of the Li-yu-tan earthdam subjected to the Chi-Chi earthquake, initial stress state before earthquake was computed by *FLAC* 5.0 performing stage construction, steady state seepage and static equilibrium. Material properties of the dam were estimated with the field and laboratory test results during construction. After the initial state was obtained, the dam was then subjected to both horizontal and vertical accelerations of the earthquake. Acceleration and displacement time histories and permanent displacement of the dam can be obtained. The results were compared with the field measurement.

### 2.1 *Procedure of the simulation*

The procedures of this study are as follows:

1 Data collection – Available experimental and monitoring data related to the dam were collected. The data were examined and selected for

estimating the engineering properties for numerical analyses of the dam.

2 Constitutive law of the dam materials – The Mohr-Coulomb soil model was adopted with the *FLAC* built-in “Sigmoidal 4” equivalent-linear hysteretic model to analyze the dynamic responses of the dam. The constitutive law was calibrated by the test results of the dam performed by the Central Water Resources Office (1997). Static triaxial compression tests, dynamic triaxial compression tests and field dynamic tests were used to obtain the input parameters.

3 Static analyses – The mid-section of the Li-yu-tan dam was modeled as a two dimensional grid. The dam was formed by the simulation of staged construction using 20 layers. Uncoupled with mechanical analysis, steady state seepage of the dam for a 60 m water level was then performed. Uncoupled with groundwater seepage analysis, the static equilibrium state of the dam was then computed. These analyses obtained the following results: 1) stress distribution after dam construction, 2) pore water pressure distribution at steady state seepage, and 3) initial stress state before earthquake.

4 Dynamic analysis – By using the same grid and the initial stress, the dam was assigned the Chi-Chi earthquake acceleration time-history. This study input the horizontal and vertical acceleration time-history simultaneously. The distributions of the maximum acceleration, pore water pressure and permanent displacement, were obtained. In addition, specific locations were monitored for time histories of acceleration, velocity, and displacement, pore pressure.

5 Evaluation of permanent displacement – The permanent displacement of the dam after the earthquake shaking was compared. In addition, accelerations time histories at top of the dam and its Fourier were discussed.

6 Parametric study for retaining water levels – A parametric study was performed for high water level (90 m) and low water level (30 m) to observe the differences in dynamic responses among the three different water levels.

## 2.2 *Numerical model*

### 2.2.1 *Simulation of dam construction*

The core of the earthdam is mainly impermeable clayey materials (CL, ML, GC, ML). The upstream and downstream shells are permeable to semi-permeable materials made of gravel and clean river-bed materials. A grid for the dam was generated by sequentially adding 20 layers of zones as Figure 1. The purpose of the construction simulation is to obtain a reasonable stress state for the dam while it was still dry (before retaining water). When a layer was added, a new static equilibrium for the dam was carried out. The material properties of the dam were classified into the upstream shell, core and downstream shell. The engineering properties for the simulation are listed in Table 1 based on the field and laboratory test data (Central Water Resources Office 1997).

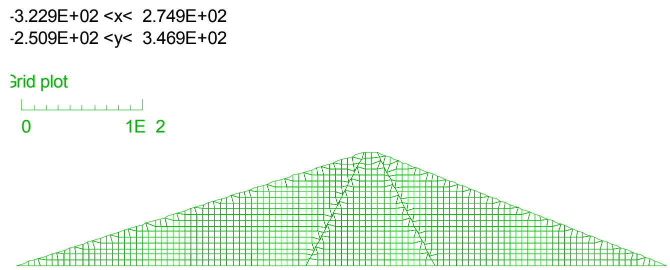


Figure 1. The mesh of Li-yu-tan earthdam in *FLAC*.

Table 1. The material parameters of the earthdam (Central Water Resources Office 1997).

| Zone | Shear Modulus $G$, (Pa) | Permeab. $K_h$, (cm/sec) | Poisson’s Ratio $\upsilon$ | $c$ (kPa) | $\phi$ deg. |
|---|---|---|---|---|---|
| Upstream shell | 4.0e8 | 5e-6 | 0.34 | 14.5 | 41 |
| Core | 5.7e8 | 1e-7 | 0.45 | 83.5 | 27 |
| Down-stream shell | 4.0e8 | 5e-6 | 0.33 | 30.5 | 35 |

### 2.2.2 *Steady-state seepage after retaining water*

The retaining water level of Li-yu-tan earthdam was 60 m when the Chi-Chi earthquake struck. Therefore, the “baseline case” of this study assumed a retaining water level of 60 m. Steady state seepage analysis was performed using the “saturated fast flow scheme” that reduces the computational time and gains accuracy (Itasca 2005). The boundary condition at the interface between dam and the retaining water was assigned saturated (S = 100%). The rest of the boundaries, which did not “contact” water, were assigned pore water pressures of zero. The steady state seepage calculation was performed without interaction with mechanical equilibrium and the result is shown in Figure 2. Comparing the results with the field measurement data (Central Water Resources Office 2000a), the trends of the phreatic surface are similar.

### 2.2.3 *Initial static stress condition before earthquake*

After seepage analysis, initial static state before earthquake was computed. The effective stress of the dam was altered due to buoyancy. The buoyancy force corresponded to the phreatic surface. Therefore, the effective stresses in upstream shell are smaller than those in downstream shell. The vertical effective stress distribution is shown in Figure 3. For this computation, the "fluid" calculation scheme was "closed". Also, in order not to interact pore pressure with mechanical volume changes, the water bulk modulus was set to zero. After the initial static stress calculation, the dam showed a slight movement in an upstream direction due to the stress reduction in upstream shell.

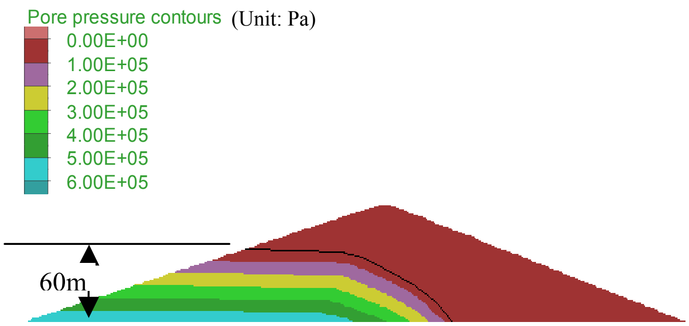


Figure 2. The pore pressure distribution after the seepage analysis.

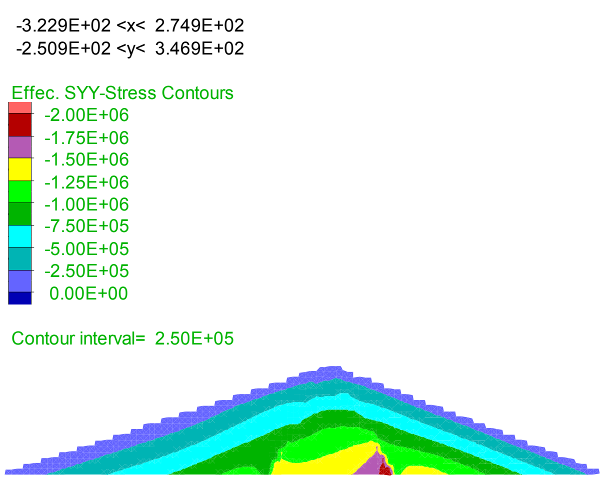


Figure 3. Initial y-stress state after seepage analysis and static equilibrium.

### 2.2.4 *Dynamic analysis*

The Chi-Chi earthquake acceleration time histories recorded at the bottom and central section of Li-yutan dam (Central Water Resources Office 2000) were selected for this study. The horizontal acceleration component that is perpendicular to the long axis of the dam and the vertical component were both adopted. Before input, the acceleration time histories were filtered under 5 Hz to reduce the chance of numerical instability. In addition, baseline corrections for the acceleration time histories were made for zero velocity and displacement after integration. The 45-second horizontal and vertical acceleration waveforms are shown in Figures 4 & 5.

To account for shear modulus reduction while dynamic shear straining, the equivalent-linear model, "Sigmoidal 4", which is built-in in *FLAC* 5.0, was adopted to fit the reduction curve of normalized shear modulus ($G/G_{max}$) versus shear strain ($\gamma$). This study used the curves obtained from test results of dam materials (Central Water Resources Office 1997). These curves with the fittings of "Sigmoidal 4" model are shown in Figure 6. The $G_{max}$ values in the numerical model were assigned according to field shear wave test results as shown in Figure 7 (Central Water Resources Office 1997) referring to the initial static stress state obtained previously. After a few numerical trials, Rayleigh damping of 5% was assigned in addition to the hysteretic damping for better fitting. The duration of the dynamic analysis is 50 seconds, which is five seconds more than the duration of the input acceleration (45 seconds). The additional 5 seconds is a tried result in this study for the earthquake vibration to die out.

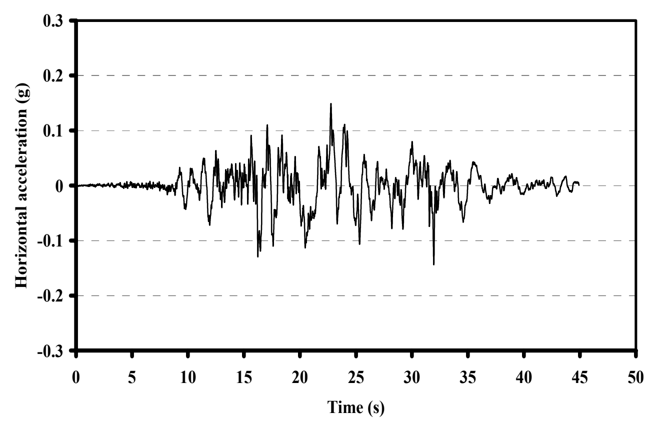


Figure 4. The monitored horizontal acceleration time history (base of the dam).

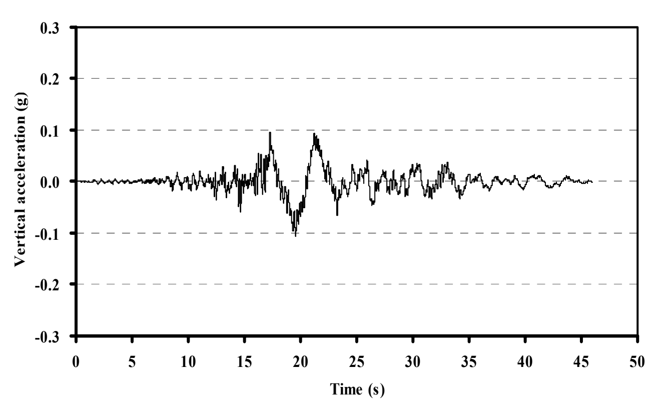


Figure 5. The monitored vertical acceleration time history (base of the dam).

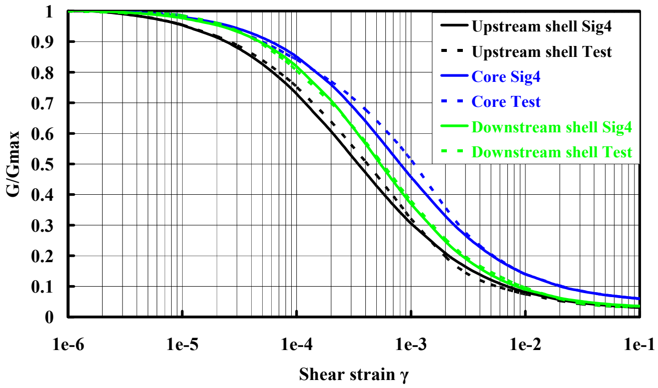


Figure 6. Shear modulus reduction curves fitted by the Sigmoidal 4 model.

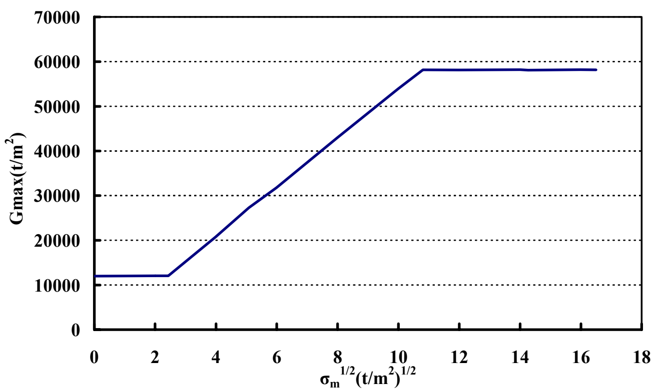


Figure 7. $G_{max}$ test results of Li-yu-tan earthdam.

The permanent deformed mesh after the 50-second earthquake is shown in Figure 8. The dam mostly deformed toward the upstream side with a maximum displacement of 4.7 cm. The dam surface deformation field measurement after the earthquake is listed in Table 2 with the calculated permanent displacement. The calculated displacement at the crest is fairly close to the field-measured data. However, larger discrepancies appear at the mid-height of upstream and downstream shells. The calculated values tend to be smaller. This could be due to the fact that the numerical model did not include the foundation rock layer, which is shale and slate. The foundation layer may deform too. In addition, the triangle model of the dam was fixed at the base that constrained the deformability of the dam and prevented sliding of dam materials at base.

The computed horizontal and vertical acceleration histories at the crest of the dam are compared with the recorded ones as shown in Figures 9-12. The computed horizontal and vertical peak accelerations are 0.28g and 0.13g, which are close to the recorded peak accelerations, 0.24g and 0.15g, respectively.

Through Fourier power spectra of acceleration histories, frequency content of vibration can be further observed and compared. The corresponding spectra are shown in Figures 13-16.

Table 2. Comparisons of the calculated permanent displacement at the surface of dam with the measured data.

| | Displacement of upstream shell (mid-height) | | Displacement of Crest | | Displacement of downstream shell (mid-height) | |
|---|---|---|---|---|---|---|
| | Horiz. | Vert. | Horiz. | Vert. | Horiz. | Vert. |
| Measured Displacement[1] | -2.7 ~ -3.9 | -5.4 ~ -6.8 | -0.7 ~ -4.3 | -5.0 ~ -7.9 | 1.8 ~ 2.9 | -2.6 ~ -3.4 |
| Calculated Displacement | -1.9 | -0.1 | -1.3 | -4.3 | 0.4 | 0.3 |

[1]From Central Water Resources Office (1999).
Negative signs (-) represent horizontal displacement toward left or vertical downward displacement.

By comparing Figures 13 & 14, the spectra of calculated horizontal acceleration are higher than those of recorded acceleration. It could be that the assignment of shear modulus of the dam materials was too high causing a higher calculated peak horizontal acceleration and a higher peak spectrum. However, the frequencies of the peak spectra in the plots are very close.

For vertical acceleration, the spectra characteristics (Fig. 15 & 16) are very close in both peak spectra and frequencies.

An additional computation was performed without applying the Sigmoidal 4 model for dam materials. The results of the horizontal acceleration history and the spectra are shown in Figures 17 & 18. They can be compared with Figures 9 & 13, respectively. The peak acceleration became higher and is about 0.32 g. There is a very high peak value of 1.15e3 *cm/sec* in the Fourier spectra. It can be concluded that without Sigmoidal 4 model, the dam material is not "weakening" according to strain level, and thus energy is not properly dissipated.

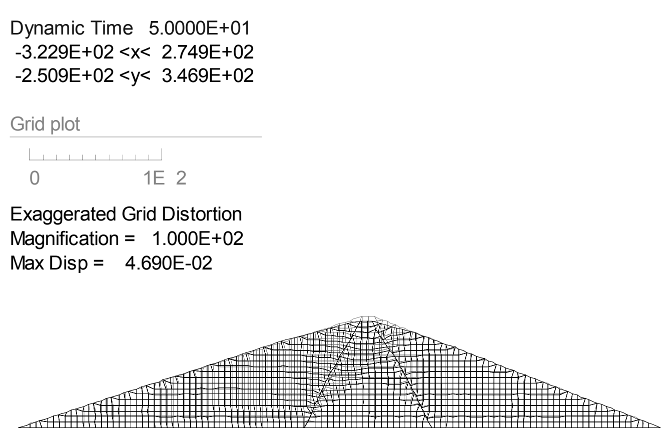


Figure 8. Grid distortion after Chi-Chi earthquake (with 100 times magnification).

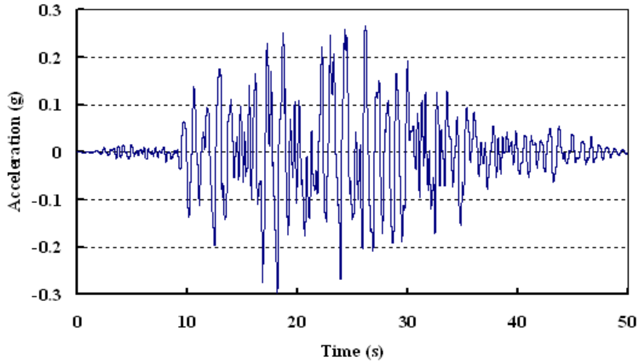

Figure 9. Calculated horizontal acceleration at the crest of the dam.

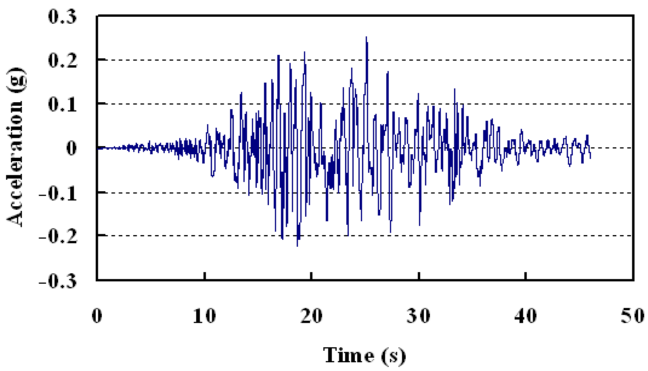

Figure 10. Recorded horizontal acceleration at the crest of the dam.

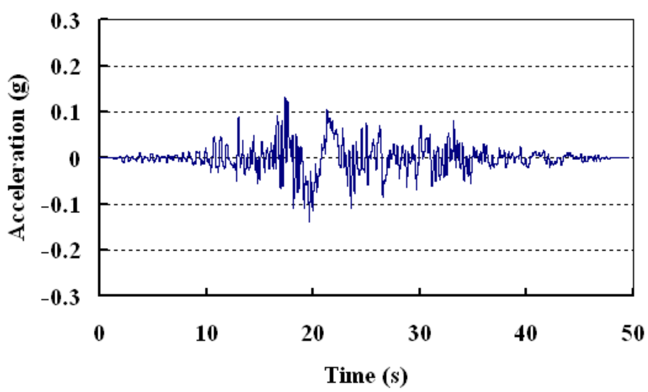

Figure 11. Calculated vertical acceleration at the crest of the dam.

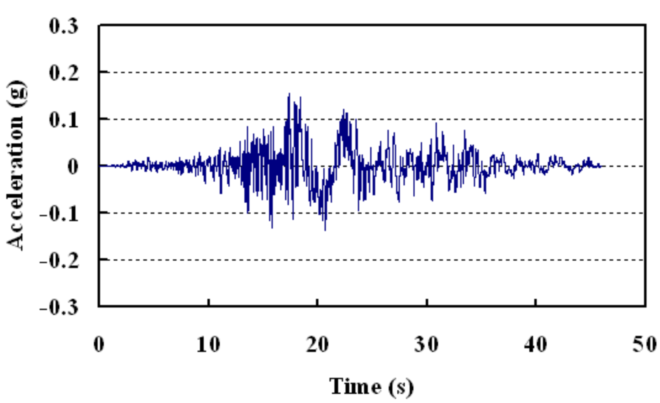

Figure 12. Recorded vertical acceleration at the crest of the dam.

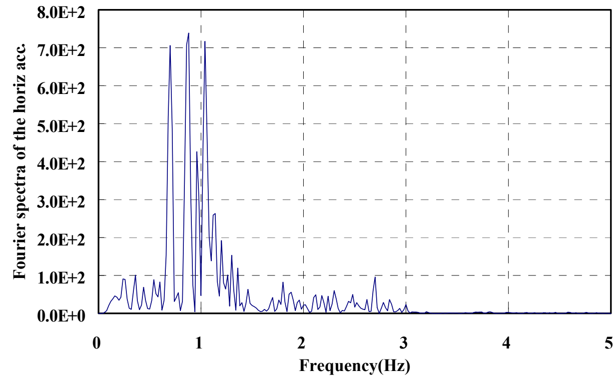

Figure 13. The Fourier spectra of the calculated horizontal acceleration of the crest of the dam.

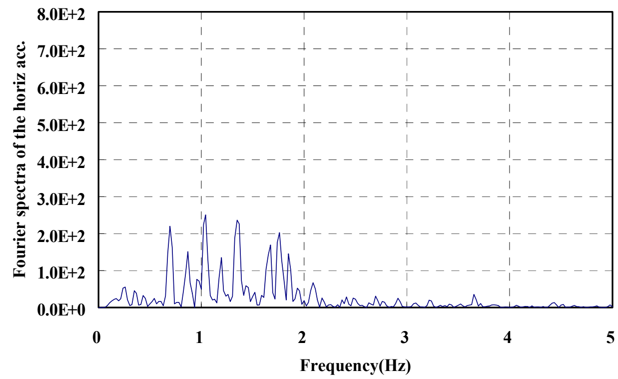

Figure 14. The Fourier spectra of the recorded horizontal acceleration of the crest of the dam.

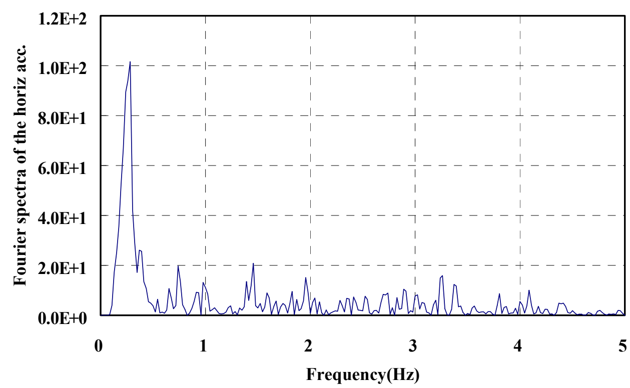

Figure 15. The Fourier spectra of the calculated vertical acceleration of the crest of the dam.

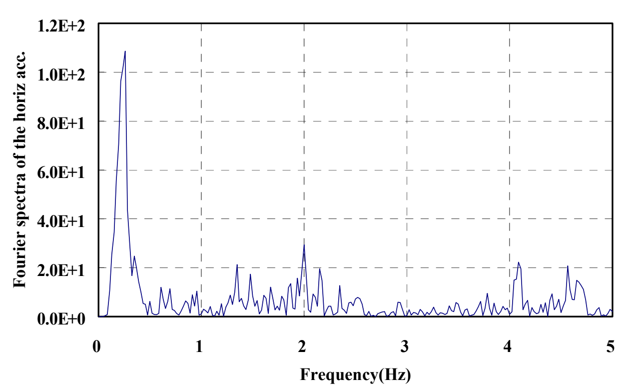

Figure 16. The Fourier spectra of the recorded vertical acceleration of the crest of the dam.

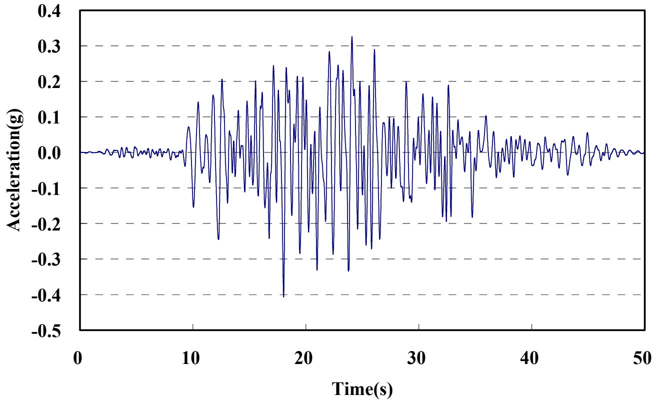


Figure 17. Calculated horizontal acceleration at the crest of the dam – without the Sigmoidal 4 model.

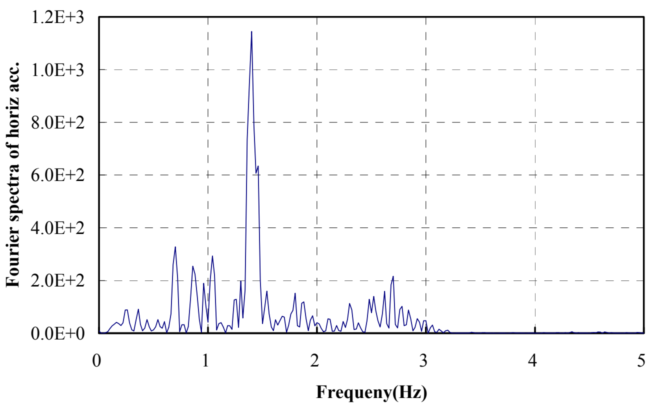


Figure 18. The Fourier frequency spectra of the calculated horizontal acceleration of the crest of the dam – without the Sigmoidal 4 model.

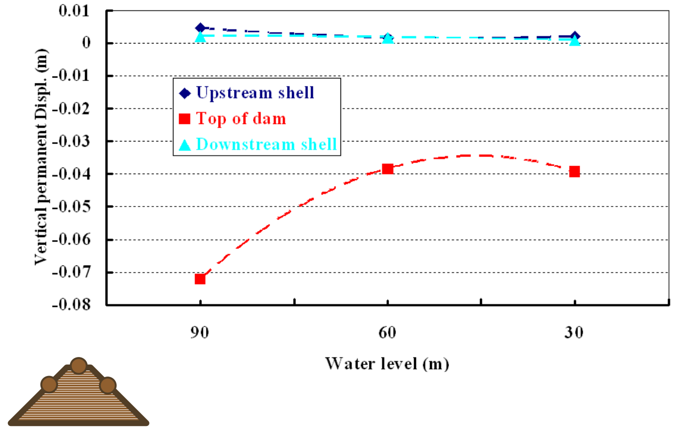


Figure 19. Vertical permanent displacement at the crest (top), upstream and downstream shells of the dam for water levels of 90, 60 and 30 m.

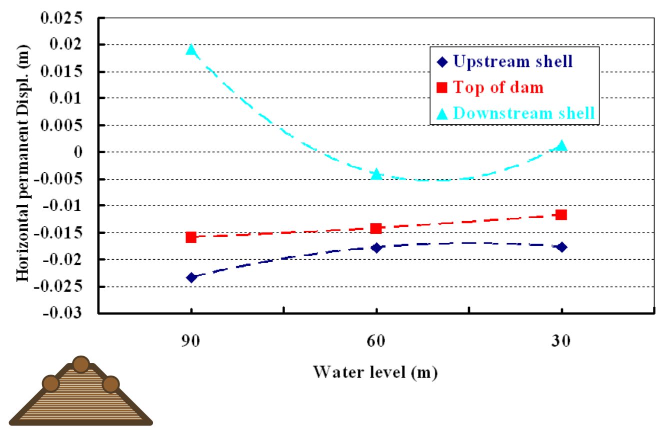


Figure 20. Horizontal permanent displacement at the crest (top), upstream and downstream shells of the dam for water levels of 90, 60 and 30 m.

## 3 PARAMETRIC STUDY RESULTS OF RETAINING WATER LEVELS

For comparison purpose, the retaining water levels were varied between 30m (the lowest water lever of the dam) and 90m (the highest water lever of the dam). The same dynamic analysis procedures were performed. Both vertical and horizontal permanent displacement values for the three water levels were plotted in Figures 19 and 20, respectively. They show a general trend that the higher the retaining water is, the larger the permanent displacement would be, except the case of the horizontal permanent displacement of 60m water lever in Figure 20.

Maximum relative horizontal and vertical displacement between the crest and base of the dam during the 50 seconds of shaking can be calculated as shown in Figure 21. It shows that the maximum relative displacement during the earthquake increases significantly with increasing water levels.

Figure 22 shows that the peak horizontal acceleration is not much affected by water levels, while the peak vertical acceleration increases significantly at 90 m of water level.

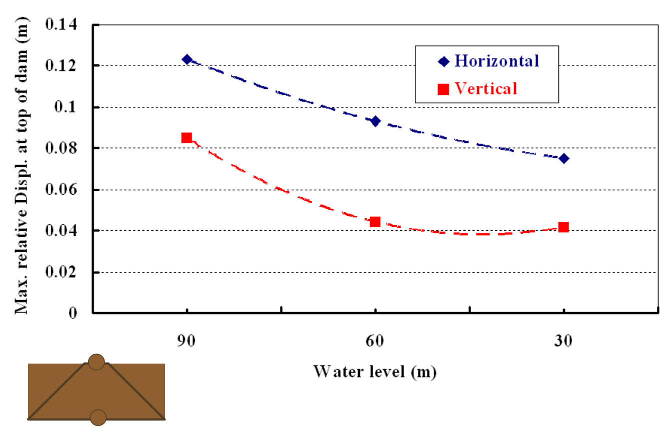


Figure 21. Maximum relative horizontal and vertical displacement between the crest and the base of the dam during the 50 seconds of earthquake shaking for water levels of 90, 60 and 30 m.

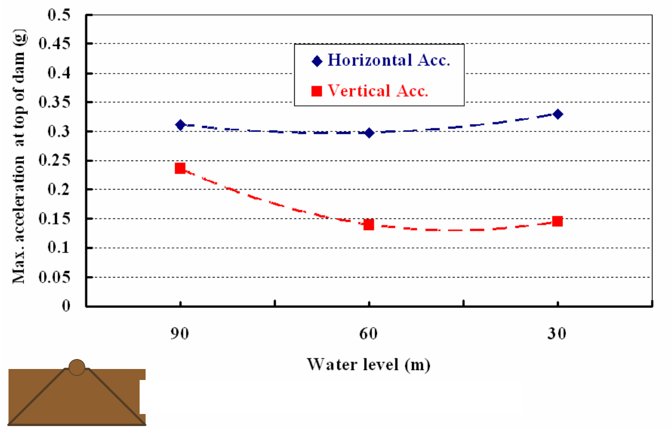


Figure 22. Peak horizontal and vertical accelerations at the crest of the dam during the 50 seconds earthquake shaking for water levels of 90, 60 and 30 m.

## 4 CONCLUSIONS

This study used *FLAC* 5.0 to analyze the dynamic response of Li-yu-tan earthdam subjected to the 1999 Chi-Chi earthquake (ML = 7.3) in Taiwan. The analyses included construction phase, steady state seepage, initial static stress state, and dynamic analysis. In addition, a parametric study for the retaining water levels was performed. A summary of this study follows:

– The numerical scheme used in analyzing dynamic response of Li-yu-tan dam is straightforward and the results are mostly reasonable after the comparison with monitored field data.
– The spectra comparison of the vertical accelerations at crest is satisfied. The spectra of calculated horizontal acceleration at crest are higher than those of monitored acceleration. However, the frequencies of the "peaks" in the spectra plots are very close.
– The *FLAC* built-in equivalent-linear hysteretic model, Sigmoidal 4, can effectively account for shear modulus reduction and energy dissipation during dynamic straining.
– Generally, a higher retaining water level could cause larger permanent displacement and larger relative displacement between the crest and base of the dam than those of lower retaining water level.

## ACKNOWLEDGEMENT

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