集集地震中日月潭水庫頭社壩之震態分析

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摘要

本文分析日月潭水庫頭社壩受到 921 **集集地震之動態反應，分析的方法採用**(1) **半分析試驗法**(the semi-analysis-testing method)**，與** (2) **簡易法**(the Makdisi-Seed simplified method)**等二法。半分析試驗法須配合** FLUSH **與** ISBILD **程式，分別以等值線性與土壤殘留勁度弱化假設來估算動態反應、變形趨勢與坡面滑移量。簡易法則應用震態疊加與加速度反應譜來推估最大壩頂加速度與坡面永久滑移量。半分析試驗法可得詳細之分析結果，而簡易法可在數小時內得到具代表性的動態反應，其結果大致上與半分析試驗法之結果相當。**

關鍵字：土石壩、地震、地震反應、永久變形、FLUSH**。**

The Seismic Performance of Tousheh Dam During the Chi-Chi Earthquake

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ABSTRACT

The seismic performance of Tousheh earth dam of the Sun-Moon Lake in the central Taiwan during the Chi-Chi Earthquake on September 21, 1999 was analyzed by using two methods, the semi-analysis-testing method and the Makdisi-Seed simplified method. The semi-analysis-testing approach uses the FLUSH program to perform equivalent-linear dynamic response analysis for the dam. The acceleration records of the nearest seismogram station (TCU079) was chosen as the input motion. The permanent deformation of the dam after the earthquake was calculated using the finite element program, ISBILD. This method investigates the dynamic response of the dam in details and it provides a rational estimations on deformation pattern of the dam and the permanent displacements of the crest and slopes. The Makdisi and Seed method is a much simpler approach to estimate the crest acceleration using modal superposition and the acceleration response spectra of the input motion. Strain-dependent soil properties were used for iterating the average shear strain of the dam. The Makdisi and Seed method for permanent displacements of the potential sliding surfaces of the dam was approximated using a concept modified from the Newmark method. The maximum crest acceleration and permanent displacements of the slopes can then be estimated within hours. The results were compared with that obtained from the semi-analysis-testing method as well as the observed deformations.

Keywords: earth dam, earthquake, seismic response, permanent deformation, FLUSH.

1. INTRODUCTION

Tousheh dam of Sun-Moon Lake is one of the two earth dams which form the reservoir of the most important hydro-electrical power generation system in Taiwan. The total installation capacity is over 2,750MW of its four power stations, including Mingtan and Minghu pumping storage schemes. Therefore, the safety of the dams is crucial. Tousheh dam is a roller compacted earth fill dam with a concrete cut-off wall constructed in the 1930s. The construction method was very popular in the past but it is considered out-of-date from the viewpoint of the modern dam building technology. The original design considerations including the magnitude of design earthquake and the method of assessment are also not very well-documented. On September 21, 1999 the Chi-Chi earthquake occurred and the epicenter is about only 10 km to the west of the dam site. The dam was subjected to very strong shaking with a PGA value in excess of 0.4g. The performance survey of the dam was also made by the maintenance authority. This provides a unique opportunity in examining the reliability of the methods for seismic performance analysis of earth dam.

This paper presents the results of seismic analysis of Tousheh dam due to the Chi-Chi earthquake using two methods, the semi-analysis-testing method and the Makdisi-Seed simplified method. The semi-analysis-testing approach uses the FLUSH program to perform equivalent-linear dynamic response analysis for the dam. The acceleration records of the nearest seismogram station (TCU079) is chosen as the input motion. The permanent deformation of the dam after the earthquake was calculated using the finite element program, ISBILD. This method investigates the dynamic response of the dam in details and it provides a rational estimations on deformation pattern of the dam and the permanent displacements of the crest and slopes.

The Makdisi and Seed method (Makdisi and Seed, 1978) is a much simpler approach to estimate the crest acceleration using modal superposition and the acceleration response spectra of the input motion. The maximum crest acceleration and permanent displacements of the slopes can be estimated within hours. The results were compared with that obtained from the semi-analysis-testing method as well as the observed deformations.

2. THE DESIGN OF TOUSHEH DAM AND EARTHQUAKE RECORDS

Tousheh dam is a roller-compacted, zoned dam with a central RC wall as the impervious seepage barrier. The maximum height of the dam is 20 m and the crest length is 166 m. The width of the crest is 6 m. On the upstream slope, there is a fill zone formed by dumping the excavation tailings during the construction of Mingtan intake structures. A typical section of Tousheh dam is shown in Figure 1.

In 1992, a safety inspection and evaluation program was conducted for Tousheh dam. In the program a series of static and dynamic laboratory tests for the dam materials were conducted as well as the field shear wave velocity measurements. The results were used as the fundamental input parameters for this case study (Sinotech, 1992). The index properties and strength parameters of the dam materials are summarized in Table 1.

Post-earthquake observation show that the dam developed settlements in the crest and at the interface between the fill and upstream slope. There is slightly bulging at the lower part of the downstream slope. The maximum crest settlement is around 24 cm or 1.2% of the maximum dam height. The settlement at the fill/shell interface is about 30 cm with the separation/crack width ranging from several centimeters to 30 cm. There may be some cracks at the concrete face panels of the upstream shell which was covered by the fill. However, it is not possible to inspect. The deformation pattern of the dam after Chi-Chi earthquake and the locations of cracks are illustrated in Figure 2.

Although there was no strong motion monitoring device installed directly at the dam site, the nearest seismograph station (TCU079) recorded the Chi-Chi earthquake acceleration history and registered a horizontal PGA of 0.58g. The station was set up by the Central Weather Bureau and is located only 0.5 km from the dam. Therefore, this case study used the Chi-Chi earthquake records of this station to evaluate the safety of Tousheh dam. Because the dynamic response analysis is assuming a two dimensional plane strain problem with only horizontal shaking, the recorded acceleration history would need to be adjusted to a direction acting perpendicular to the longitudinal axis of the dam. This is done by trajectory projection method using the E-W and N-S acceleration components. The final input acceleration waveforms used in the analysis is shown in Figure 3, which has a PGA values of 501 gals.

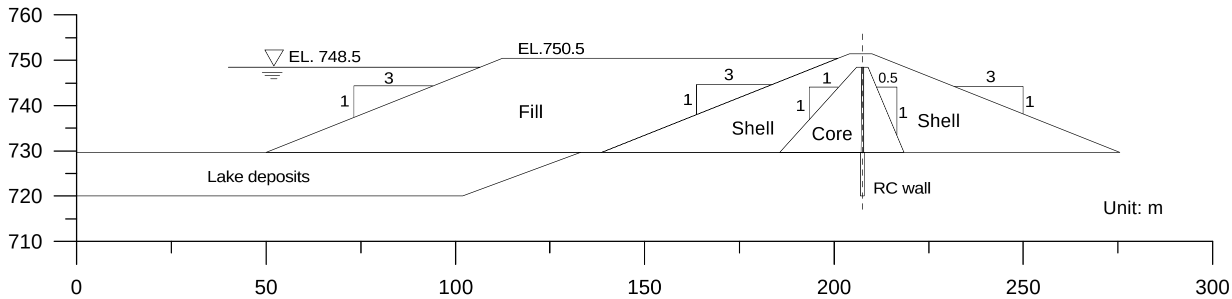


Figure 1. A typical section of Tousheh dam

Table 1 The index properties and strength parameters of the dam materials

Zone	SPT-N value	Dry Density (t/m^3)	PI (%)	c' kg/cm^2	ϕ' deg.	Unified Soil Classification
Core	10~27	1.60~1.80	9~15	0~0.33	25~35	SC, CL
Shell	11~24	1.68~1.85	0~13	0~0.02	33~35	SC, SM
Fill	-	1.86	-	0.20~0.23	38~39	GM, GP

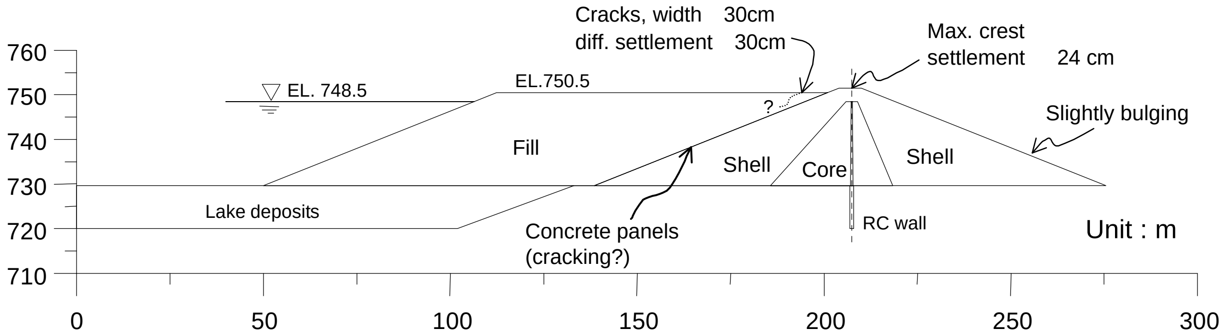


Figure 2. Measured settlements and locations of cracks after Chi-Chi earthquake

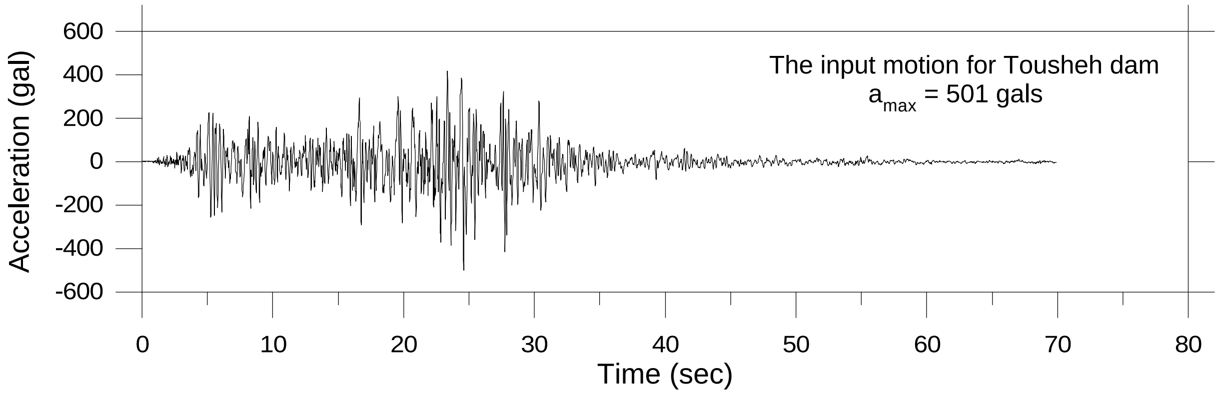


Figure 3. The Chi-Chi earthquake input motion for Tousheh dam

3. RESULTS OF ANALYSIS USING THE SEMI-ANALYSIS-TESTING METHOD

The semi-analysis-testing approach proposed by Seed and his co-workers was adopted for the analysis. By this approach, dynamic responses of the dam were calculated using the equivalent linear elastic analysis program, FLUSH. The softening of soil mass during earthquake was modeled by varying the strain level dependent shear modulus and damping ratio. Acceleration, strain and shear stress time histories can be traced throughout the dambody for the duration of earthquake. For example, the calculated acceleration time history at the dam crest using the Chi-Chi input motion (as in Figure 3) is shown in Figure 4. After the numerical simulation, the peak accelerations can be obtained for each nodal points of the dam and they were presented by the contour plot of peak accelerations as shown in Figure 5. By which, the overall dynamic response of the dam during Chi-Chi earthquake can be evaluated.

Beside the dynamic response analysis, the performance of the dam shall be further evaluated for the three major potential failure modes due to earthquake, including liquefaction, permanent deformation, sliding of the dam slopes. The embankment of Tousheh dam was constructed by compacting low to medium high plasticity materials. Therefore, liquefaction is unlikely to occur and there is no evidence of liquefaction observed in the field also. To assess the overall settlement and deformation of the dambody, the residual strain potential approach was used. In this approach, the time history of shear stresses was converted to equivalent uniform stress cycles. Residual strain potentials of the dam materials were evaluated through laboratory tests. Based on the residual strain potentials, the overall deformation of the embankment was calculated by using the modified stiffness method suggested by Kuwano and Ishihara (1988). The finite element program, ISBILD, was employed to calculate the permanent deformations due to the Chi-Chi earthquake. The numerical results of the deformation pattern is shown in Figure 6. The settlement at the crest is about 23 cm which is slightly smaller than the observed 24 cm in Figure 2. The maximum settlement of the fill is calculated as 64cm. Although no survey data in the upstream slope are available, the maximum movement is expected to occur in the fill. Because the fill was formed by dumping tailings of excavations and was not compacted, their large settlement/sliding is likely to appear. Overall the permanent deformation analysis is reasonable and the results agree well with the observed patterns.

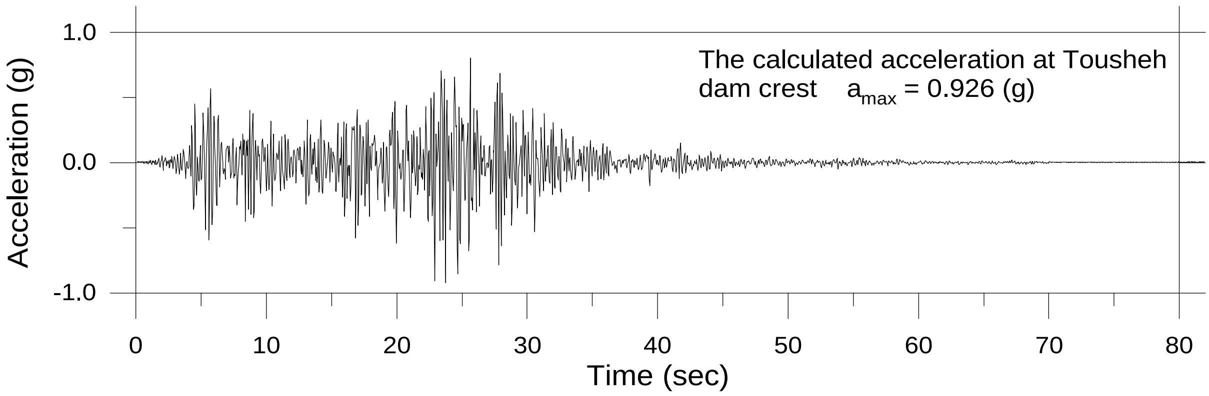


Figure 4 The acceleration response at the dam crest

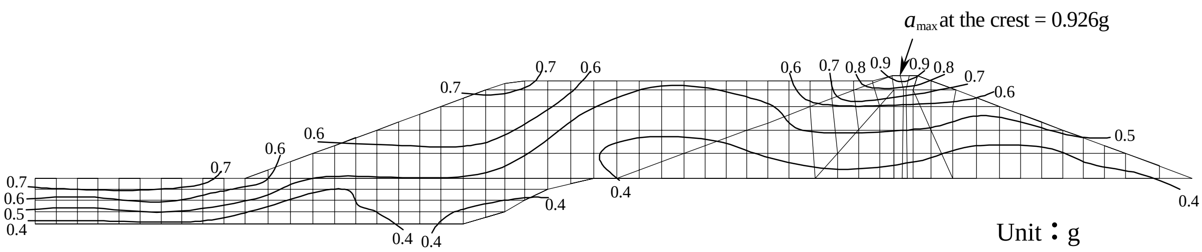


Figure 5. The contour plot of peak accelerations of Tousheh dam during Chi-Chi earthquake

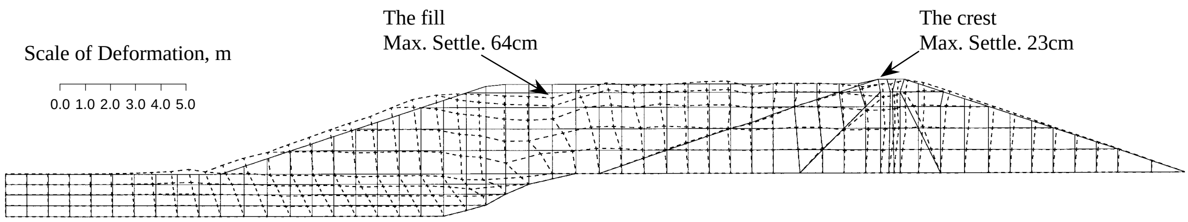
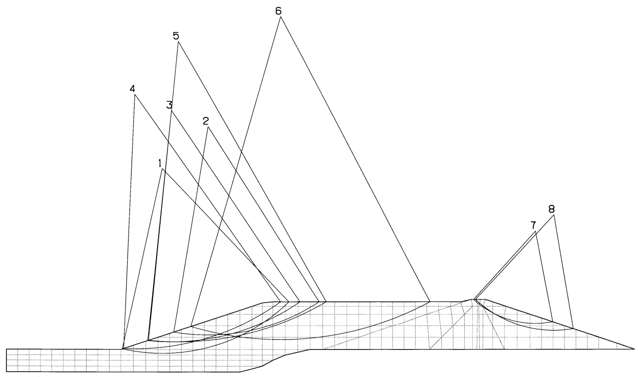


Figure 6. Estimated permanent deformation of Tousheh dam after Chi-Chi earthquake

To assess the slide movement in slopes, sliding block analysis originally proposed by Newmark (1965) was carried out. In the analysis, the acceleration time histories together with its initial static stresses in a potential sliding block was checked for reaching the yield acceleration and then double integrated the acceleration to obtain the sliding movement when the accelerations exceed of yield acceleration. The results of analysis for the 8 potential sliding blocks for Tousheh dam are shown in Figure 7. For the sliding block No. 5 the permanent horizontal displacement is estimated about 50cm. Significant horizontal movements were calculated mostly in the fill zone as it was not compacted

4. RESULTS OF ANALYSIS USING THE MAKDISI AND SEED METHOD

The Makdisi and Seed method is a simple approach to estimate the crest acceleration using modal superposition and the acceleration response spectra of the input motion. Strain-dependent soil properties were used for iterating the average shear strain of the dam. This method uses the concept modified from the Newmark method (1965). The maximum crest acceleration and permanent displacements of the slopes can be estimated relatively quick. The method was detailed described in the papers of Makdisi and Seed (1978, 1979).



No. of sliding blocks	1	2	3	4	5	6	7	8
Horizontal Displ. (cm)	-14.7	-28.6	-41.7	-9.5	-48.9	-18.5	+0.6	+1.3

Note: sliding to right (+); sliding to left (-)

Figure 7. Calculated displacement of sliding blocks

Table 2. Calculation of the crest acceleration and sliding displacement by the Maksidi and Seed method.

Basic data of Tousheh Dam:

Gmax avg= 100000 kPa PGA= 0.511 g

Unit wt.= 20 kN/m^3 Height= 20 m

First Iteration

Step 1 Assuming Gamma: Gamma avg= 0.0001

Step 2 find shear wave velocity

G/Gmax= 0.9 G= 90000 kPa D= 0.07

Shear Vel= 210.11 m/sec

Step 3 The three modal periods

T_1= 0.249 sec T_2= 0.108 sec T_3= 0.069 sec

Step 4 Spetral accelerations corresponding toT_1, T_2 and T_3

Sa1/PGA= 1.8 Sa1= 0.92 g

Sa2/PGA= 1.6 Sa2= 0.82 g

Sa3/PGA= 1.1 Sa3= 0.56 g

Step 5 Max acceleration at the crest: a_{max}= 1.77 g

Step 6 Gamma avg: Gamma avg= 0.0000813

2nd iteration:

Step 1 Assume Gamma: Gamma avg= 0.0000813

Step 2 Find shear wave velocity

G/Gmax= 0.91 G= 91000 kPa D= 0.06

Shear Vel= 211.27 m/sec

Step 3 The three modal periods

T_1= 0.248 sec T_2= 0.108 sec T_3= 0.069 sec

Step 4 Spetral accelerations corresponding toT_1, T_2 and T_3

Sa1/PGA= 1.8 Sa1= 0.92 g

Sa2/PGA= 1.6 Sa2= 0.82 g

Sa3/PGA= 1.1 Sa3= 0.56 g

Step 5 Max acceleration at the crest: a_{max}= 1.77 g

Step 6 Gamma avg: Gamma avg= 0.0000804

Step 7 Iterations completed - accept the averaged strain as 8E-5

Step 8 Determine yield acceleration

y= 16 m y/H= 0.8

ky= 0.45 g (assumed yield acceleration of the potential failure surface)

Step 9 Find k_{max}

k_{max}/a_{max}= 0.4 (Fig. 6.46, Abramson, 1996) k_{max}= 0.710

Step 10 Find permanent displacement

k_y/k_{max}= 0.634 Magnitude of the Gi-Gi EQ= 7.3

The permanent displacement is estimated as 1 ~ 10 cm. (Fig. 6.47, Abramson, 1996)

The crest acceleration is estimated as 1.77g.

For Tousheh dam the crest acceleration and the permanent sliding displacement were calculated as shown in Table 2 following the steps suggested in Abramson et al (1996) with some judgements. The required response spectra and the dynamic properties are presented in Figure 8 and 9. The permanent sliding displacement was estimated ranging from 1 to 10 cm and the crest acceleration was estimated as 1.77g. The estimation of the permanent sliding displacement in the upstream shell of the dam (not in the fill zone) is considered in good agreement with the observed deformation pattern. The acceleration is much higher than the 0.926g obtained from the semi-analysis testing method. The estimated large acceleration could be due to: 1) the acceleration response spectra values are large at the low periods range (0.1~0.2 sec) because of high frequency components and noise in the input motion; 2) the input motion is adjusted from the surface free-field station TCU079, therefore, the acceleration could be much stronger than those at the base of the dam; 3) The method assumed 1D vibration, thus the confinement of the fill zone was not well accounted. The two dimensional program FLUSH takes care of these concerns.

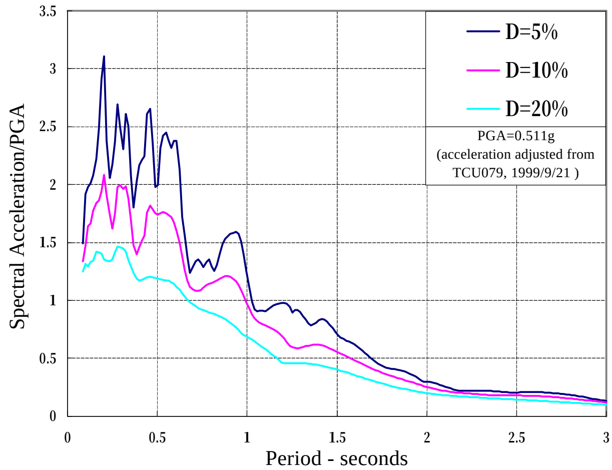


Figure 8. The response spectra for Tousheh dam

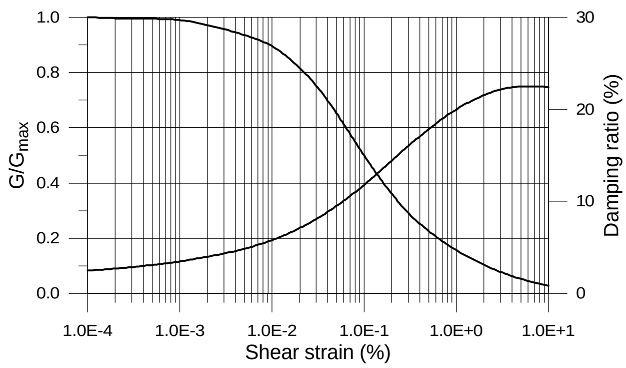


Figure 9. The averaged dynamic properties of Tousheh dam

5. CONCLUDING REMARKS

This paper presents the results of seismic performance analysis of Tousheh dam due to the 921 Chi-Chi earthquake using two methods, the semi-analysis-testing method and the Makdisi-Seed simplified method. From the results, it appears that the semi-analysis-testing method can predict the seismic performances of the well-compacted earth dam very well, both in the deformation and sliding movement of the embankment slopes. The much simpler Makdisi and Seed method gave a higher estimation of the acceleration in the crest. The estimation of the sliding displacement is considered good. The Makdisi and Seed method can provide a quick estimation for earthquake response of dams and its prediction is much improved from the conventional pseudo static method.

Although the seismic analysis methods have been improved from pseudo static analysis to full dynamic response analysis, it is still difficult to predict realistic dynamic performance of a dam without the feedback of field observations. Performing case studies for the responses of Tousheh dams during Chi-Chi earthquake provides a valuable opportunity in evaluating the methods of seismic analysis.

There are at least 9 dams in Taiwan strongly shaken by the Chi-Chi earthquake (Chern and Chang, 2000). It should be worthwhile to perform the Makdisi and Seed method for the dams to calibrate the charts published by Makdisi and Seed (1978) for establishing localized experiences for quick evaluation of the dams in Taiwan.

For dams built in narrow canyons, the transverse cracks due to 3D effect is also an important damage mode. Two dimensional analysis may be not good enough for a proper prediction. Nevertheless, the shaking in vertical direction appeared very strong during Chi-Chi earthquake. Therefore, the effect of vertical vibration should be considered. A true 3-dimensional analysis and physical modelling may be necessary for very important dams.

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