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Seismic Safety Analysis of Earth Dam — Case History Studies

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SEISMIC SAFETY ANALYSIS OF EARTH DAM - CASE HISTORY STUDIES

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ABSTRACT

The method of seismic safety analysis for earth dam was examined by using actual performances of earth dams during the Chi-Chi Earthquake. Results of analysis under design earthquakes were also collected and compared with the performance records of earth dams. From the results of these studies, it appears that the Seed-Lee-Idriss approach can provide reasonable predictions on the dynamic responses and post-earthquake performance of well-compacted earth dam.

KEYWORDS

Seismic Safety Analysis, earth dam, Maximum Acceleration, Settlement, cracking

INTRODUCTION

Taiwan is located on the collision boundary between the Eurasian Plate and Philippine Sea Plate. The Philippine Sea Plate is subducting along the Ryukyu Trench in the north and the Eurasian Plate underthrusts the Philippine Sea Plate along the Manila Trench in the south. The Philippine Sea Plate is moving northwestwardly at a rate of 7~8 cm/year relative to the Eurasian Plate. The tectonic setting causes the rapid uplifting of Taiwan island and the development of numerous faults. The distribution of the 51 active faults, which have been identified to date, along with the locations of existing major dams, is illustrated in Fig. 1. From historical earthquake records, more than 8 damaging earthquakes with magnitudes over 6.5 in the Richter scale, including the Chi-Chi earthquake, which occurred on September 21, 1999 and the 3 after-shocks, have occurred in the last century. With the occurrence of so many large earthquakes on such a small island, it is rather astonishing. Therefore, seismic safety is one of the most important considerations in the design of dams in Taiwan.

In the design processes, identification of causative faults and analysis of dam performance during earthquake play the most crucial role in seismic safety assessment. Although the Chi-Chi Earthquake caused no severe damage to the existing dams, the rupture of the Chelungpu Fault, identified as a non-active fault previously, raised more concerns on the safety of dams by the general public, academics and practicing engineers as well. This caused severe obstacles for implementing the reservoir project which is of vital importance for a country with very little water resources. Moreover, the development of geotechnology to date does not allow the design engineer to accurately predict the performance of dams during earthquake. Judgement based on experience still plays an important role in safety assessments. Therefore, it may be useful to assess the reliability of the current seismic safety analysis method based on actual case histories of dam performance during earthquakes.

In this paper, the records of earthquake performance of earth dams collected from Taiwan and abroad and the results of seismic safety analysis carried out for dams in Taiwan were used to assess the reliability of the method most widely used in the seismic safety assessment of earth dams.

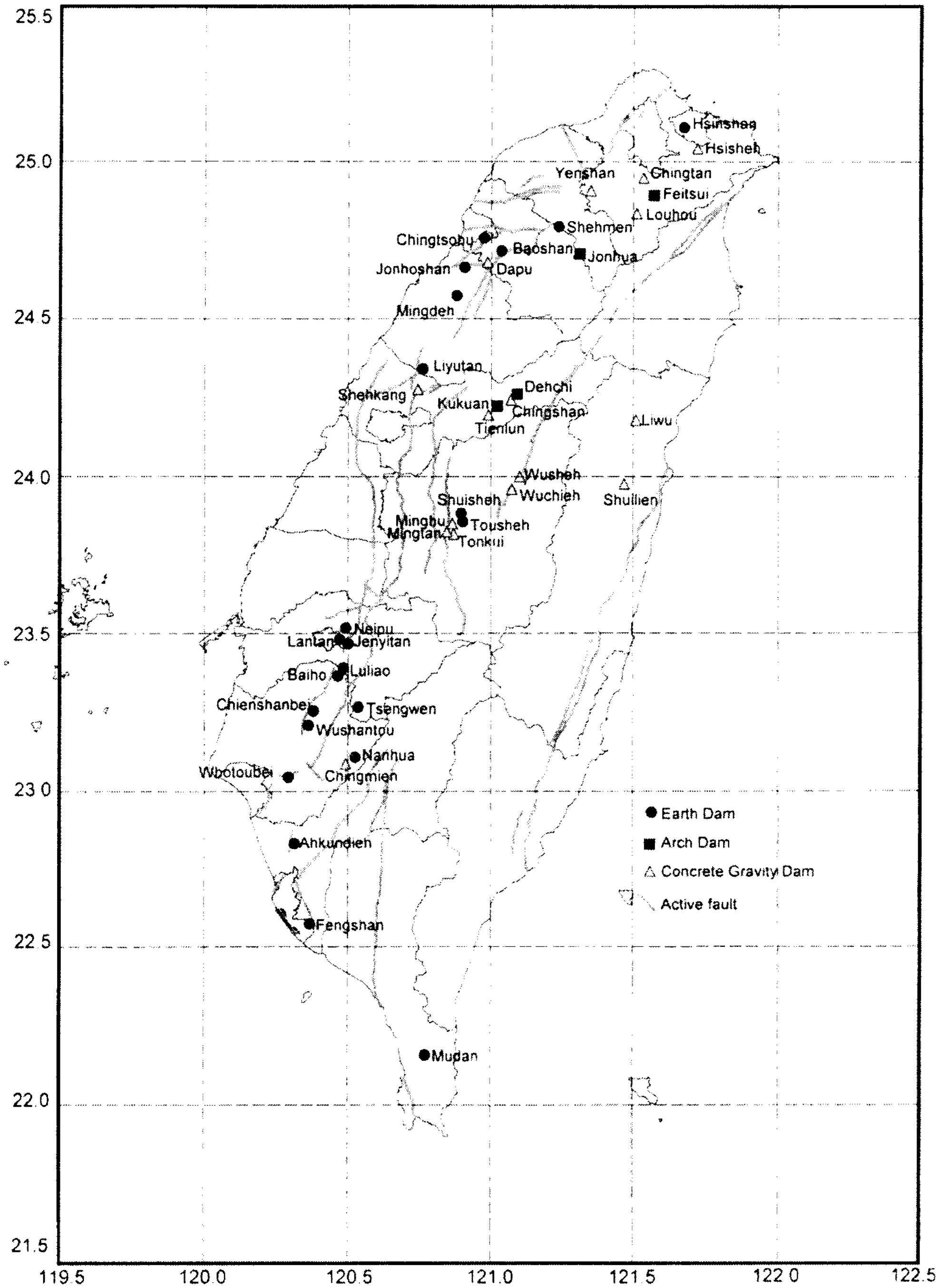

Fig. 1 Locations of major dams and identified active faults

EFFECTS OF EARTHQUAKE ON EARTH DAM

From previous experiences, the types of damage done to earth dam due to earthquake may include:

(I) Sliding of embankment slope or foundation

(II) Cracking of embankment
  a. longitudinal cracking
  b. transversal cracking

(III) Reduced freeboard due to excessive settlement

(IV) Leakage due to cracking caused by fault shearing

(V) Breaching of dam due to over-topping of reservoir water caused by seismic water waves

(VI) Other unidentified causes

According to statistical data from Resendiz et al (1978), more than 60% of earthquake damages belong to type (I). This type of damage is mostly caused by soil liquefaction in dams constructed by the hydraulic fill method or dams constructed on soft foundation. The types of seismic damage to roller-compacted dams constructed by modern dam-building techniques is mostly type (II). Excessive deformation of the dam body, which may lead to leakage of water and loss of freeboard, is the main concern.

Currently, there are 22 major earth dams with height over 15 m in Taiwan. All dams, with the exception of Wushantou Dam which was constructed by the semi-hydraulic fill method, are roller-compacted, zoned dams with central impervious clay core or concrete cut-off wall. During the Chi-Chi Earthquake, several dams in central Taiwan have experienced very strong shaking. The performance records for some dams, along with the recorded or estimated maximum acceleration at dam sites, are listed in Table 1. The most commonly observed behavior is the settlement and deformation of the dambody accompanied by the development of cracking. Among them, the Shuisheh dam of Sun-Moon Lake reservoir, which experienced PGA value in the order of 0.58g, developed 0.66% of crest settlement and 7 longitudinal cracks in the dam crest and upper part of upstream slope with widths ranging from less than 1 cm to 7 cm and the maximum length over 300m. However, the Liyutan dam, which was shaken by a relatively low acceleration level around 0.05g, developed transversal cracks near the abutments even though the crest settlement is only 0.1% of the dam height. Both dams are considered to develop type II behavior. Therefore, the major concern on the safety of well-compacted earth dams is associated with the settlement and deformation of the dambody.

METHOD OF SEISMIC SAFETY ANALYSIS ADOPTED

Since the catastrophic damages due to the 1964 Niigata Earthquake and Alaska Earthquake, tremendous progress on the understanding of soil behavior during earthquake shaking have been made. The method of seismic safety analysis has also evolved from the traditional psuedo static analysis to the full dynamic analysis. Numerous methods, including the Seed-Lee-Idriss' semi-analytical and testing method and the more advanced effective stress methods, have been developed. Unlike the semi-analytical and testing method proposed by Seed-Lee-Idriss, effective stress analysis approach can calculate the development of pore pressure and deformation during the process of shaking. However, due to the difficulty in obtaining the model parameters, the Seed-Lee-Idriss approach is still the most widely used method in assessing the safety of earth dam during earthquake by practicing engineers. Several major earth dams in Taiwan have been assessed by using this approach in the 1990s. The flow chart of the method adopted is shown in Fig. 2. As shown in Fig. 2, three potential failure modes, i.e., Newmark's block sliding, post-earthquake stability due to pore pressure rise and settlement and deformation of dam, were considered. In this paper, only the settlement and deformation of dambody are discussed.

CASE STUDIES OF EARTH DAMS DURING CHI-CHI EARTHQUAKE

To assess the reliability of seismic safety analysis approach adopted, two case histories, namely the Shuisheh Dam and Liyutan Dam, were studied for their responses during the Chi-Chi Earthquake. The results of analysis were then compared with the observed performances.

Table 1 Observed Performances of Earth Dams during Chi-Chi Earthquake

Case No.	Name	Height (m)	a_{max} at dam site	Observed Performance
1.	Tsengwen	133.0	<0.1g*	δ_{max} =0.002% no abnormal condition
2.	Liyutan	96.0	0.05g	δ_{max} =0.1% cracking near abutments
3.	Nanhua	87.5	0.037g	δ_{max} =0.01% no abnormal condition
4.	Yunhoshan	62.5	<0.1g*	no abnormal condition
5.	Mudan	62.5	<0.1g*	δ_{max} =0.016% no abnormal condition
6.	Wushantou	56.0	<0.1g*	δ_{max} =0.05% no abnormal condition
7.	Baoshan	34.5	0.23g	δ_{max} =0.003% no abnormal condition
8.	Lantan	31.0	0.25g*	δ_{max} =0.08% no abnormal condition
9.	Shuisheh	30.3	0.58g*	δ_{max} =0.66%, 7 longitudinal cracks with max. width of 7cm and max. length of 300m
10.	Jenyitan	28.0	0.68g**	δ_{max} =0.1% no abnormal condition
11.	Tousheh	19.1	0.58g*	δ_{max} =1.26% no abnormal condition

Notes: δ_{max} =max. crest settlement, * denotes estimated value **denotes record of Chiayi earthquake, Oct. 22, 1999

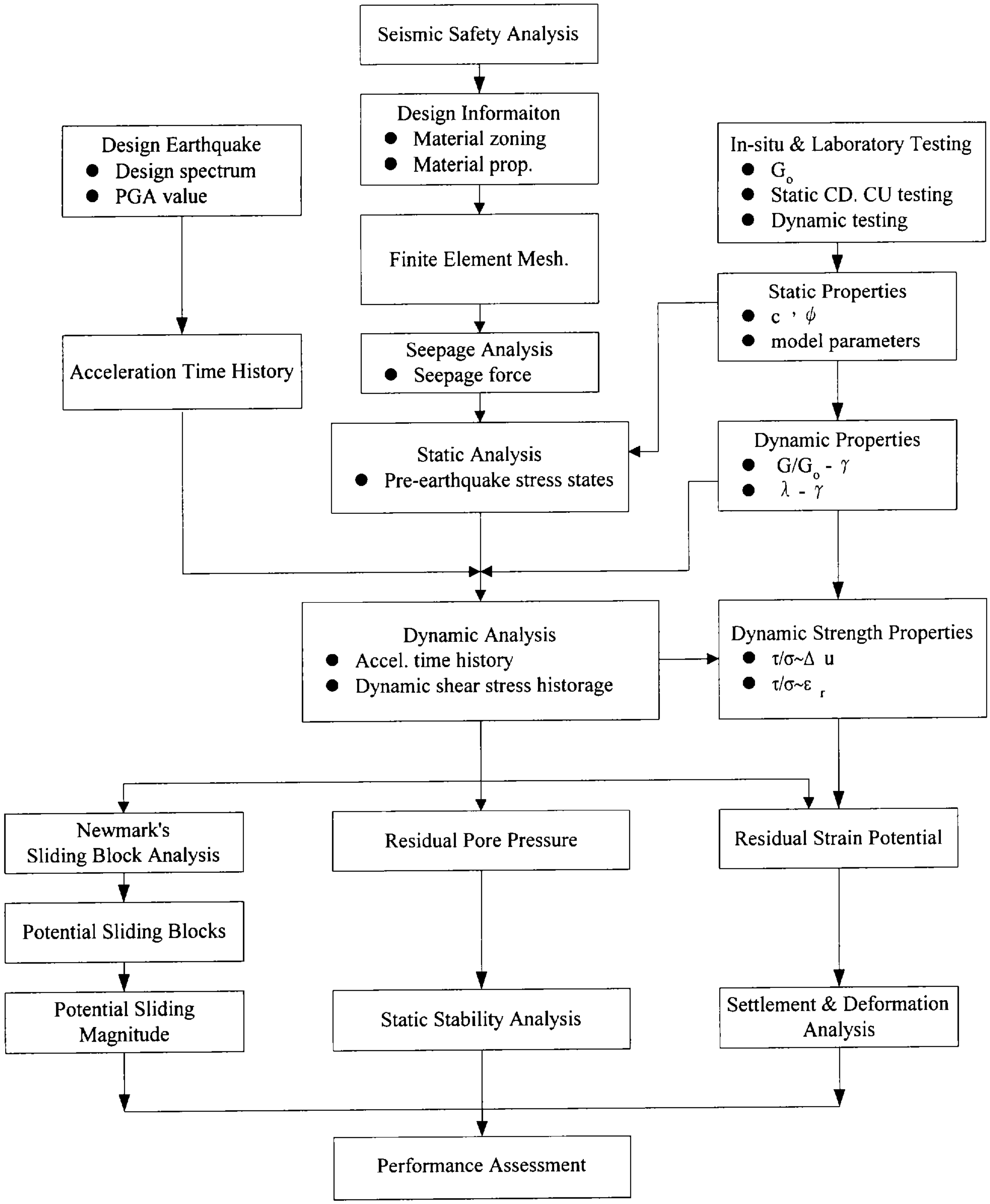

Fig. 2 Flow chart of seismic safety analysis for earth dam

Table 2 Case Histories of Recorded Earthquake Performance and Analysis Results

Dam	Dam type	Dam height (m)	a_{max} at dam foundation (g)	a_{max} at dam crest (g)	Crest settl. (%)	Notes
Tsengwen	Roller-compacted, zoned dam	133	0.15 0.42 0.03	0.26 0.69 -	0.03 0.81 0.02	Hualian EQ, 1985 Design EQ Chi-Chi EQ, 1999
Shehmen	Roller-compacted, zoned dam	133	0.36	0.82	0.45	Design JEQ
Wushantou	Semi-hydraulic fill	56	0.024 0.43	0.04 0.68	- 2.32	Hualian EQ, 1986 Design EQ
Tousheh	Roller-compacted, RC core	21.8	0.46 0.24	- 0.60	1.26 0.46	Chi-Chi QE, 1999 Design EQ
Shuisheh	Roller-compacted, RC wall	30.3	0.46 0.24	- 0.46	0.66 0.33	Chi-Chi EQ, 1999 Design EQ
Baiho	Roller-compacted, zoned dam	43.5	0.37	0.72	0.54	Design EQ
Nanhua	Roller-compacted, zoned dam	87.5	0.037 0.40	- -	0.01 0.40	Chi-Chi EQ, 1999 Design EQ
Mudan	Roller-compacted, zoned dam	62.5	0.41	0.65	0.40	Design EQ
Liyutan	Roller-compacted, zoned dam	96	0.05	0.25	0.1	Chi-Chi EQ, 1999
Baoshan	Roller-compacted, zoned dam	34.5	0.23	-	0.003	Chi-Chi EQ, 1999
Jenyitan	Roller-compacted, zoned dam	28	0.68	-	0.01	Chiayi EQ, 1999
Lantan	Roller-compacted, RC core	31	0.25*	-	0.08	Chi-Chi EQ, 1999
La Villta (Mexico)	Rockfill	60	0.072 0.039 0.017 - 0.125	0.343 0.209 0.371 0.423 0.696	0.03 0.03 0.05 0.08 0.17	Oct. 1975 EQ Nov. 1975 EQ Mar. 1979 EQ Oct. 1981 EQ Sep. 1985 EQ
El Infiernillo (Mexico)	Rockfill	146	0.084 0.087 0.120 0.132	- 0.27 0.355 0.450	0.02 0.02 0.06 0.07	Oct. 1975 EQ Nov. 1975 EQ Mar. 1979 EQ Sep. 1985 EQ
Matahina (N. Z.)	-	86	-	0.42	0.04	Mar. 1987 EQ
Namioka (Japan)	-	52	0.079	0.223	0.11	May 1983 EQ
Makio (Japan)	-	107	-	0.7~0.8	-	Sep. 1984 EQ
Miboro (Japan)	-	131	-	0.20	0.02	Aug. 1961 EQ
Del Valle (U. S.)	Earth dam	-	0.06	0.09	-	Loma Prieta EQ, 1989
Anderson (U. S.)	Zoned dam	-	0.08	0.42	-	Loma Prieta EQ, 1989
Minoogawa (Japan)	Zoned dam	47	0.135	0.242	-	Hyogoken-Nambu EQ, 1995
Gongen (Japan)	Zoned dam	32.6	0.105	0.220	-	Hyogoken-Nambu EQ, 1995

Note: *estimated value

Shuisheh Dam

Shuisheh Dam is a roller-compacted, zoned earth dam with central RC wall as the water barrier completed in 1934. The maximum height of the dam is 30.3 m, and the crest length 363.6m. The typical section of the embankment is shown in Fig. 3. According to the results of safety inspection and evaluation of the Sun-Moon Lake reservoir conducted in 1992, the index properties of dam constructing materials are:

Zone	SPT-N value	Dry Density (t/m^3)	PI (%)	Unified Soil Classification
Core	13~37	1.5~1.83	5~17	CL-ML, SC, CL
Shell	9~33	1.51~1.90	3~21	SC, SM, CL

Although no earthquake record was obtained at the dam site, the nearest seismograph station (TCU079), about 2 km away from the dam, registered 0.58g in PGA value. The acceleration time history obtained by projecting the two components of recorded motion to the direction normal to the dam axis is shown in Fig. 4. This time history will be assumed to be the input motion for the dynamic response analysis of the dam. Survey data obtained after earthquake show that the dam developed settlement in the upper part and bulging in the lower part of the embankment slope. The maximum crest settlement is around 20cm or 0.66% of the maximum dam height. The maximum settlement of the downstream slope is around 15cm, and the maximum bulging is about 2.6cm. Also observed are 7 longitudinal cracks in the crest area and the upper portion of the upstream slope with widths varying from less than 1cm to about 7cm and the maximum length over 300m.

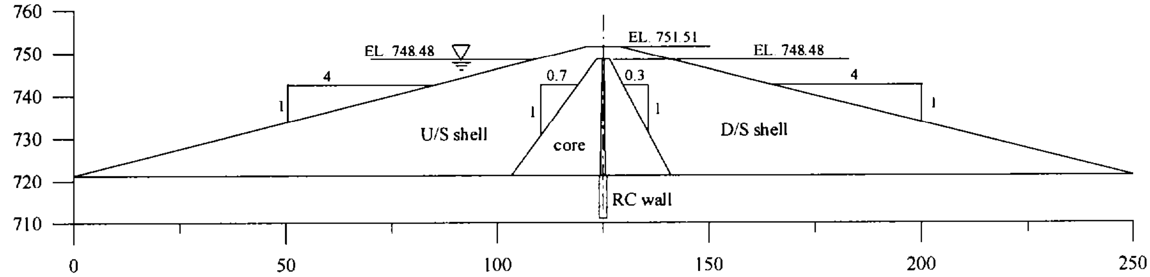

Fig. 3 Typical section of Shuisheh Dam

The calculated response at the dam crest and the distribution of maximum acceleration is given in Fig. 5. The calculated maximum acceleration response at the dam crest is around 0.705g. The calculated overall deformation of the dambody is illustrated in Fig. 6. The results show that the maximum crest settlement is around 23cm, the maximum settlement occurred in the upper part of downstream slope is around 8cm and the maximum bulging in the lower downstream slope 1cm. These results are comparable with those observed in the field. Also, the large settlement and downslope movement at the upper portion of the upstream slope might cause the occurrence of longitudinal cracks, which is also in agreement with the observed crackings in that area.

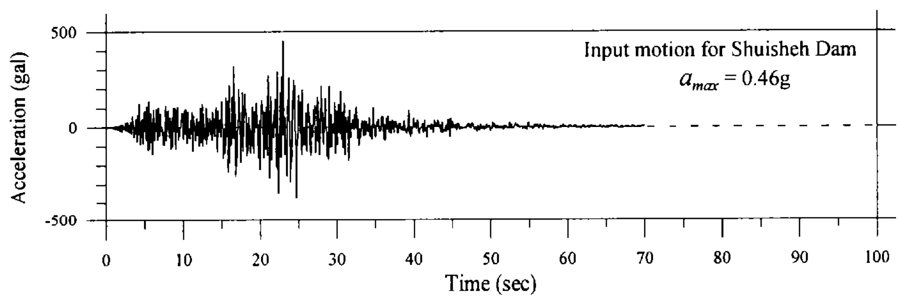

Fig. 4 Input motion for Shuisheh Dam during Chi-Chi Earthquake

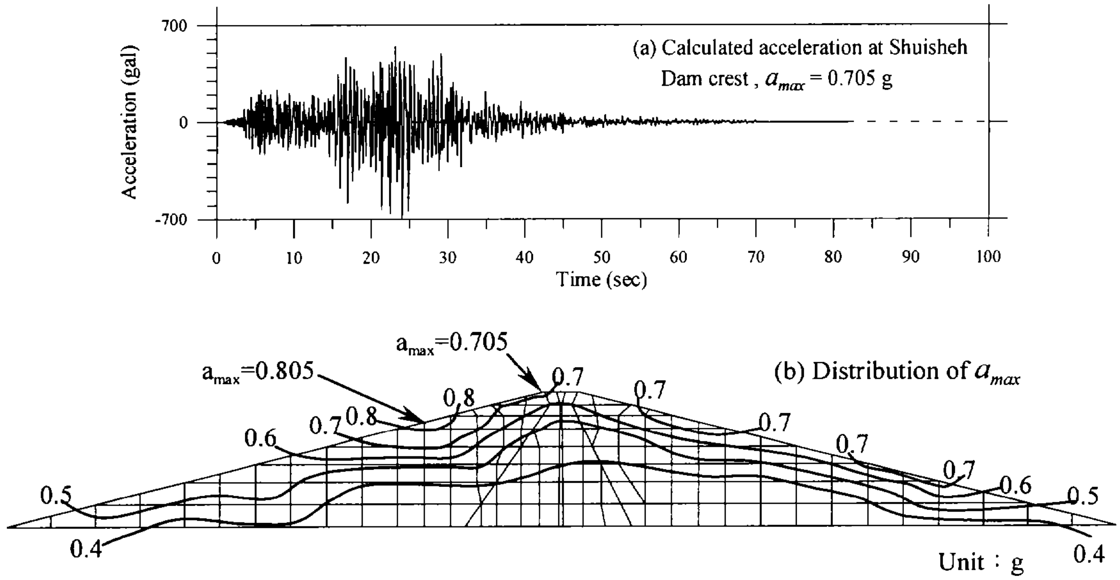

Fig. 5 Calculated dynamic response of Shuisheh Dam during Chi-Chi Earthquake

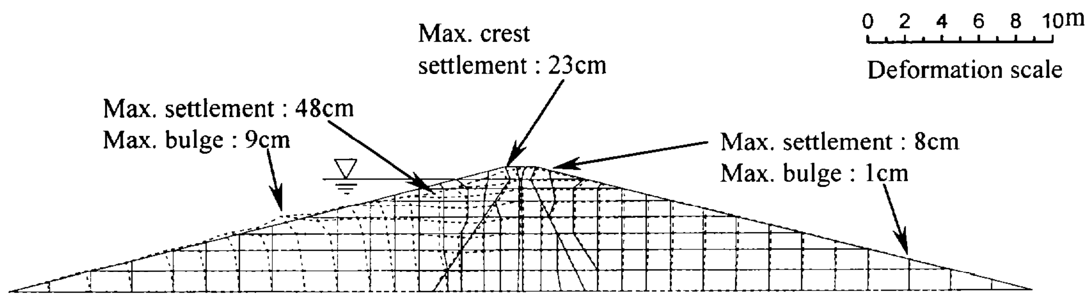

Fig. 6 Estimated deformation of Shuisheh Dam after Chi-Chi Earthquake

Liyutan Dam

Liyutan dam is a newly completed zoned dam with maximum height of 96 m and crest length of 235m. The typical section of the dam is illustrated in Fig. 7. The index properties of dam constructing materials are summarized as follows :

Zone	Bulk Density (t/m^3)	Water Content (%)	PI (%)	Unified Soil Classification
1A	2.1	16	10~20	CL-ML
1B	2.2	14	NP~8	CL-ML, SM
2	2.2	11	NP	SM~GP
3B	2.1	6	NP	GP~GW

Liyutan dam has a complete seismic monitoring system, including strong motion seismographs at the dam foundation, abutments, dam crest and downstream face. During Chi-Chi Earthquake, complete seismic records were obtained. The recorded acceleration time histories at the dam foundation and dam crest are shown in Fig. 7. Survey data obtained after the earthquake show that the maximum crest settlement is around 8cm. Near the left abutment, a transversal crack with 4~5cm wide and vertical offset of 3~5cm crossing the dam crest was observed. Similar transversal cracks were also observed on the dam crest near the right abutment.

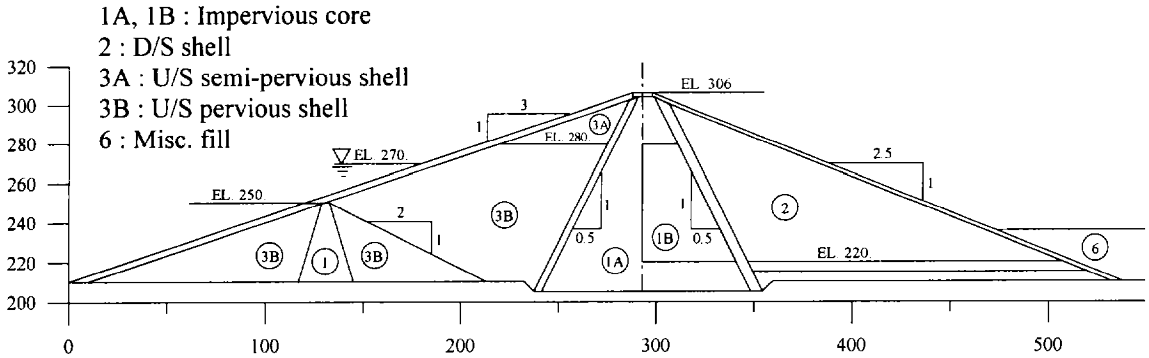

Fig. 7 Typical section of Liyutan Dam

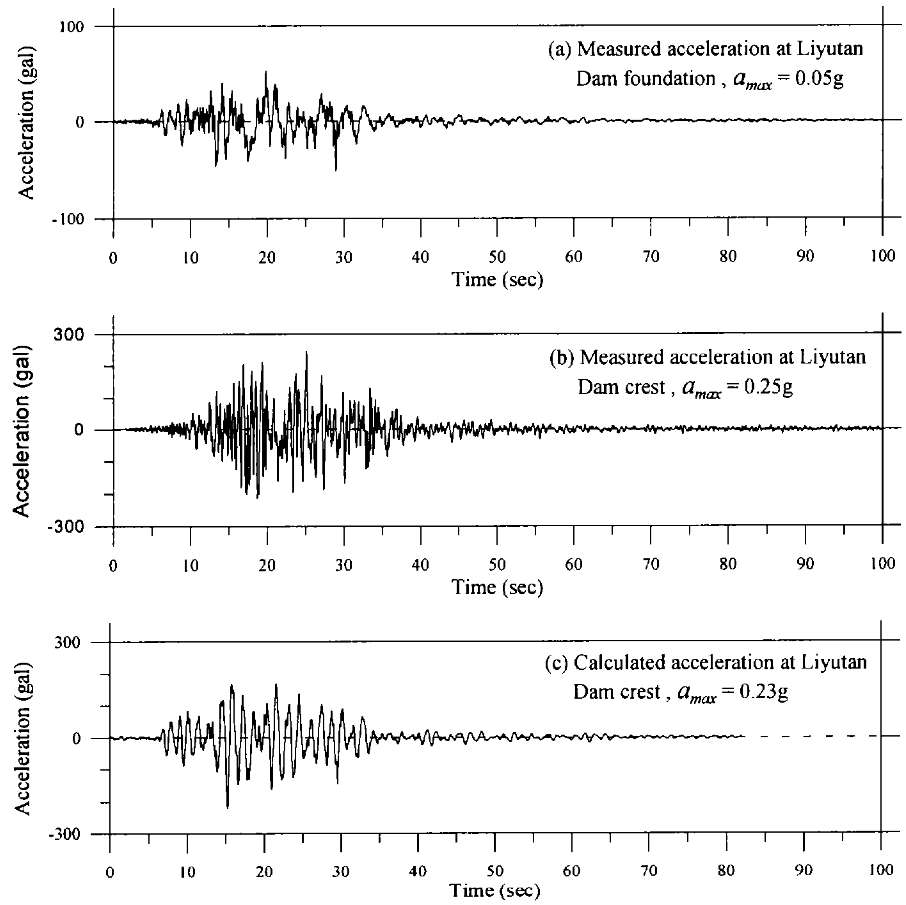

Fig. 8 Measured and calculated responses at foundation and crest of Liyutan Dam during Chi-Chi Earthquake

Due to very low width/height ratio of the dam site, the 3-D effect of abutment on dynamic responses of the dambody have to be considered. A pseudo 3-D analysis was carried out by modifying the material stiffness in order to match the recorded dynamic responses at the dam crest. The calculated responses the at dam crest are shown in Fig. 8, and the distribution of maximum acceleration is illustrated in Fig. 9. Although the calculated maximum acceleration at the dam crest is similar to the recorded value, the frequency contents of the responses are quite different. The calculated responses have predominant period of 0.7 seconds, whereas the actual records are in the range of 0.7 to 2.0 seconds. This may attribute to the omission of waves transmitted from the abutments in the 2-D analysis. Also the calculated maximum acceleration at the mid-height of the downstream slope is slightly less than the recorded 0.19g. The estimated overall deformation of the dambody after the earthquake is illustrated in Fig. 10. It shows settlements at the crest and upper portion of the slopes and bulges at the lower part of the slopes. The calculated 7cm crest settlement is quite close to the 8cm observed. The bulge in the lower portion of

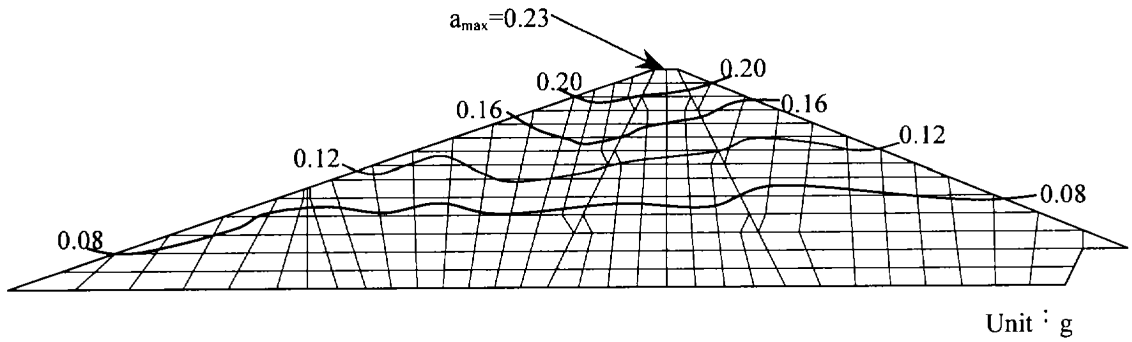

Fig. 9 Calculated maximum acceleration of Liyutan Dam during Chi-Chi Earthquake

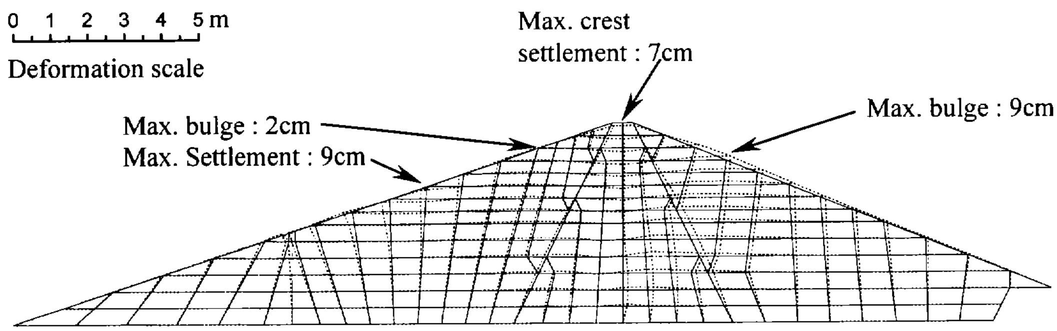

Fig. 10 Estimated deformation of Liyutan Dam after Chi-Chi Earthquake

the downstream slope is larger than the 1~2cm observed. However, they are still in the same order of magnitude.

RELIABILITY OF SEISMIC SAFETY ANALYSIS FOR EARTH DAMS

Comparing the results of analysis and actual observed performances for the two dams studied, it appears that the Seed-Lee-Idriss approach employed can capture the main features of dam performance. Dynamic responses during earthquakes and the overall post-earthquake deformation of the dambody can be predicted reasonably well. For more comprehensive comparisons of actual performances with the results of analysis, the records of case histories collected from Taiwan and abroad as shown in Table 2 were used. In these case histories, the information of PGA value at the dam site, the recorded maximum acceleration at the dam crest and the maximum post-earthquake settlement at the dam crest were collected. Several cases of seismic safety analysis under design earthquake condition were also included. By plotting the maximum acceleration and final settlement at the dam crest versus the maximum acceleration at the dam site for actual case histories and the cases analyzed for the designed earthquake condition, the results are shown in Figs. 11 and 12.

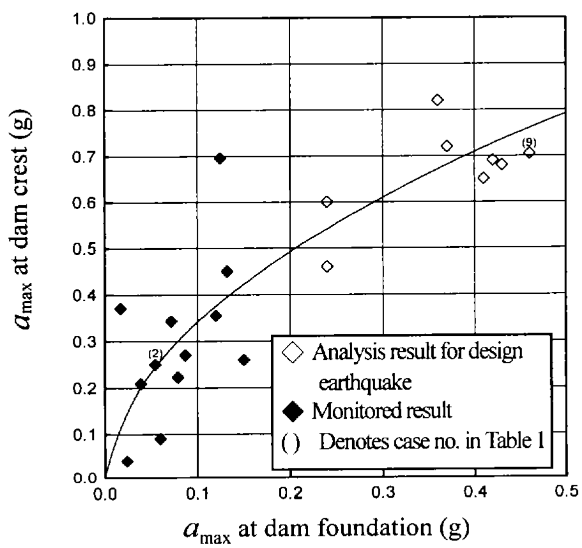

Fig. 11 Relationship between a_{max} at dam crest and a_{max} at dam foundation

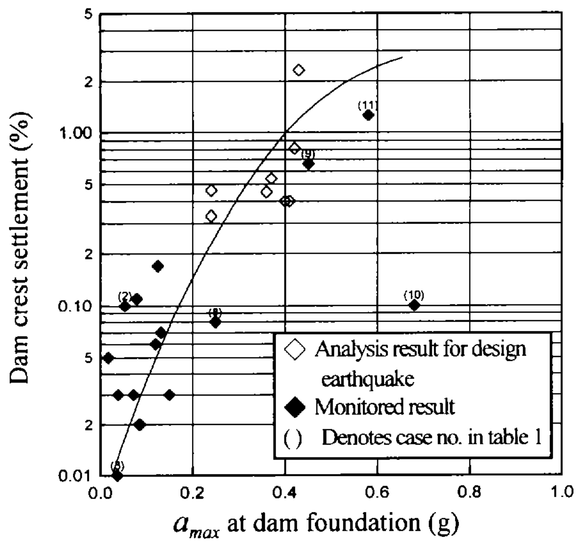

Fig. 12 Relationship between settlement at dam crest and a_{max} at dam foundation

In the figures, some scattering in results may be observed. Considering the difference in valley shape, dam height, dam design, material used, and characteristics of the earthquake, etc., in these case histories, such a scattering is natural. However, the actual records and the results of analysis are in a very similar trend. Therefore, with appropriate testing and assessment of material properties, the semi-analytical and testing approach suggested by Seed-Lee-Idriss can predict the earthquake performance of earth dam reasonably well.

CONCLUSIONS

From previous experiences on the performance of earth dams due to earthquakes, damage associated with excessive deformation of the dambody is the major safety concern for well-compacted earth dams. Comparing the results of analysis for Shuisheh dam and Liyutan dam during the Chi-Chi Earthquake, it appears that the semi-analytical and testing approach proposed by Seed-Lee-Idriss can provide a reasonably reliable prediction on the performance of well-compacted earth dams. This is also supported by the records of numerous actual case histories. However, this approach can not provide a direct assessment to the safety of dam. More research work or the establishment of empirical method based on the post-earthquake performances of dams are needed.

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