FUNDAMENTAL STUDY ON 3-D ANALYTICAL METHOD FOR EARTHQUAKE BEHAVIOR OF CONCRETE DAM AGAINST SURFACE FAULT DISPLACEMENT

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ABSTRACT :

Several dams constructed along the San Andreas Fault were damaged by the fault displacement during the San Francisco Earthquake in 1906. And, the Shih-Kang Dam was destroyed by the fault displacement during the Taiwan Chi-chi Earthquake in 1999. As for the seismic safety evaluation against strong earthquake motions, the analytical methods have been practically developed thus far. However, the analytical method for evaluating the safety against fault displacements has not been established yet. Then, I have devised the analytical method for evaluating the discontinuous behaviors of concrete dams by applying 3-D dynamic analysis method for coupled dam-joint-foundation-reservoir system in order to develop an evaluation method regarding the fault displacement. The applicability of the method proposed was examined by the analyses for concrete gravity dam.

KEYWORDS: fault displacement, 3-D analysis, discontinuous behavior, concrete dam, safety

1. PREFACE

Several dams, such as the Upper Crystal Dam (earth-fill, height 23m), the Upper Howell Dam (earth-fill, height 11m), the Old San Andreas Dam (earth-fill, height 8.5m) and so forth, constructed along the San Andreas Fault were damaged by the fault displacement during the San Francisco Earthquake in 1906 (Sherard, et.al.,1974, Leps, et.al.,1989). The Shih-Kang Dam (concrete gravity, height 25m) was destroyed by the vertical relative displacement of about 7.5m during the Taiwan Chi-chi Earthquake in 1999 (Lee, et.al,2002). The analytical methods for the seismic safety evaluation against strong earthquake motions have been practically developed thus far. However, the analytical method for evaluating the safety against fault displacements has not been established yet. Then, I have studied and devised an analytical method by applying 3-D dynamic analysis method in order to develop an evaluation method in regard to the surface earthquake fault.

Figure 1 The Shih-Kang Dam damaged by the vertical relative displacement during the Taiwan Chi-chi Earthquake in 1999

2. ANALYTICAL METHOD PROPOSED FOR EVALUATING DISCONTINUOUS BEHAVIOR OF CONCRETE DAM AGAINST SURFACE FAULT DISPLACEMENT

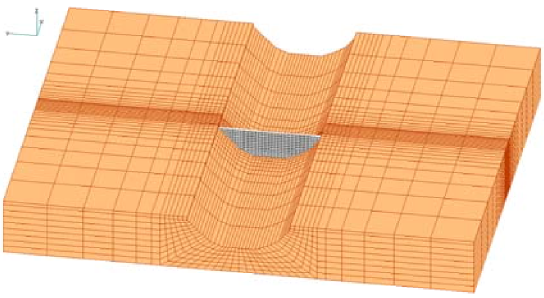
2.1 Necessity

After the 1999 Taiwan Chi-chi Earthquake, the studies on the analytical method in regard to the surface earthquake fault have been made. The analytical methods, such as the applied element method (Meguro, et.al.,2002), the non-linear stochastic finite element method (Hori, et.al.,2002), the Laglangian particle finite difference method (Konagai, et.al.,2001), and so forth have been reported for evaluating the deformation of ground and the earthquake behavior of structure. However, the analytical method in regard to dams has not developed yet. Taking such background into consideration, I have studied on the analytical method to evaluate the interaction between dams and surface earthquake fault.
r evaluating the deformation of ground and the damage of structure.

2.2 Analytical method proposed

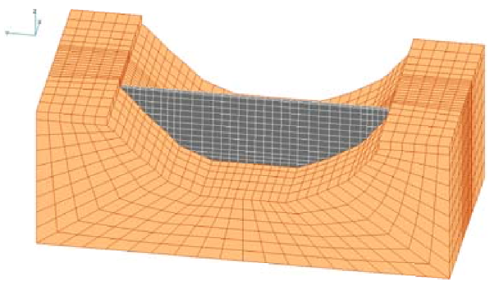
2.2.1 3-D model for a coupled dam-foundation-fault system

The 3-D dynamic analysis method for coupled dam-joint-foundation-reservoir system (Ariga, et.al.,2003) is applied for evaluating the interaction between dam and surface earthquake fault, by supposing the phenomenon as appeared in the 1999 Taiwan Chi-chi Earthquake at the Shih-Kang Dam. In this study, the boundary condition of the analytical model and the way to input an acceleration wave are contrived.
A 3-D dynamic analysis model for a coupled dam-foundation-fault system, which is made by assuming that the surface earthquake fault exists just below the dam, is shown in Figure 2 (general model). The width and the depth of the general model are 1335m and 1094m, respectively. Figure 3 shows the partial model, which was enlarged in order to indicate the analytical results. The width and the depth of the partial model are 445m and 218.88m. This analytical model was identified by the 3-D simulation analysis for the actual earthquake behavior of the existing concrete dam (the Nukabira Dam) by utilizing the earthquake motions recorded in the 1993 Kushiro-oki Earthquake (M7.8, Epicentral distance 108km) (Ariga, et.al.,2000).



Width:1335.0m, Depth:1094.4m, Height:162.0m

Figure 2 Analytical model (General model)



Width:445.0m, Depth:218.88m, Height:162.0m

Figure 3 Partial model around the dam

Table 1 Dynamic property value of dam and foundation

Items	Shear modulus N/mm^2	Density t/m^3	Poisson's ratio	Damping Factor
Rock foundation	9380	2.6	0.3	5.0 %
Dam concrete	11032	2.4	0.2	5.0 %

2.2.2 Model of the fault and the joints

The Distribution of the fault just below the dam, the contraction joints within the dam body, and the peripheral joint along the dam base is shown in Figure 4. These fault and joints are modeled by the 3-D joint element. The structural and mechanical characteristics of the 3-D joint element are shown in Figure 5 and Figure 6. In the Figure 4, the contact plane of the joint element-1 is composed of foundation rock and foundation rock. The contact plane of the joint element-2 and -3 is composed of dam concrete and dam concrete. The contact plane of the joint element -4 is composed of foundation rock and dam concrete. The dynamic property values of these 4 kinds of joint elements can be set according to the structural material and the condition of contact plane.

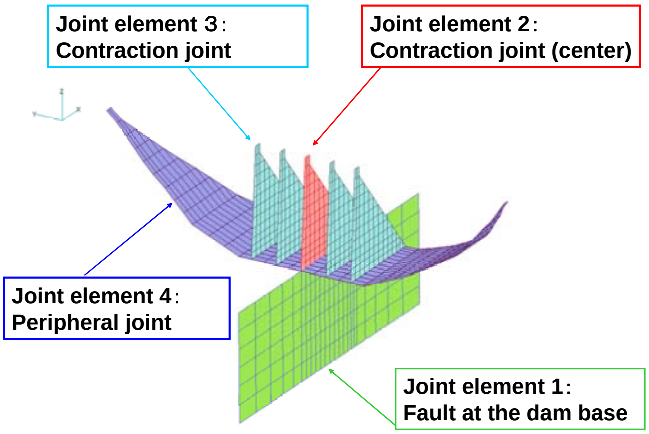


Figure 4 Distribution of the fault, the contraction joints, and the peripheral joint

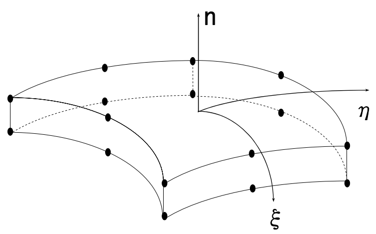
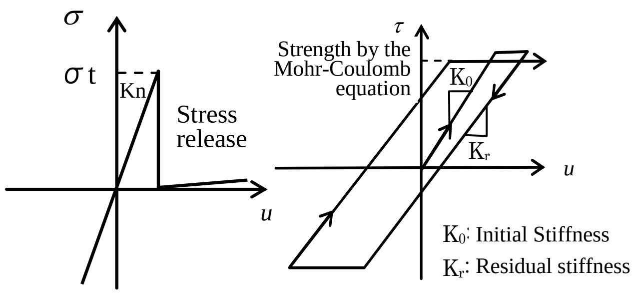


Figure 5 Structure of 3-D joint element



(1) Opening **(2) Sliding**

Figure 6 Mechanical characteristics of 3-D joint element

Table 2 Dynamic property values of the fault, the contraction joints, and the peripheral joint

Kinds of joints		Kn N/mm^2	Ko N/mm^2	C N/mm^2	φ 度	Kr	C'	φ' 度	Hj %	σt N/mm^2
1	Fault	243000	93000	0	45	1.0	0	45	5	0.01
2	Dam center	264000	110000	0	45	1.0	0	45	5	0.01
3	Dam body	264000	110000	0	45	1.0	0	45	5	0.01
4	Dam base	243000	93000	4.5	45	1.0	0	45	5	3.00

(Note : Kinds of joints correspond to Figure 4)

The dynamic property values of the fault, the contraction joints, and the peripheral joint are assumed as shown in Table 2. Kn is the dynamic shear modulus of joint plane in the normal direction. Ko is the dynamic shear modulus of joint plane in the tangential direction. C is the shear strength of joint plane. ϕ is the friction angle of joint. Kr is the dynamic shear modulus after opening or sliding. C' is the residual shear strength of joint plane after opening or sliding. ϕ is the residual friction angle of joint plane after opening or sliding. h_j is the damping factor of joint. And, σ_t is the initial tensile strength of joint. As for Kn and Ko, the values 10 times as much as the ordinal values are assumed in order to suppress the deformation at the contact plane of joint elements.

2.2.3 Boundary condition and input wave

A free boundary is set at the right half of the bottom boundary in order to simulate a fault displacement, as shown in Figure 7. An acceleration wave is input from the left half of the bottom boundary, which is rigid base. The right and left lateral boundaries are set to be a roller support in the vertical plane. The front and rear lateral boundaries are set to as a free boundary. By setting such boundary conditions, the right half of the 3-D model moves by the inertia force, and the discontinuous displacements occur along the fault.
Consequently, the behavior of dam against the fault displacement, the opening and sliding of the contraction joints and the peripheral joint, and the discontinuous displacement of dam can be analyzed.
As for the input wave, the acceleration wave shown in Figure 8 is assumed, because it is thought that it is necessary to input very strong acceleration toward one direction in order to generate the discontinuous behavior along the fault, and incidentally to generate the discontinuous displacement at the contraction joints and peripheral joint. The acceleration wave is expressed by the curve of second degree, which is convex down ward. The maximum amplitude of acceleration wave is 1G, and the duration time is 3 seconds.

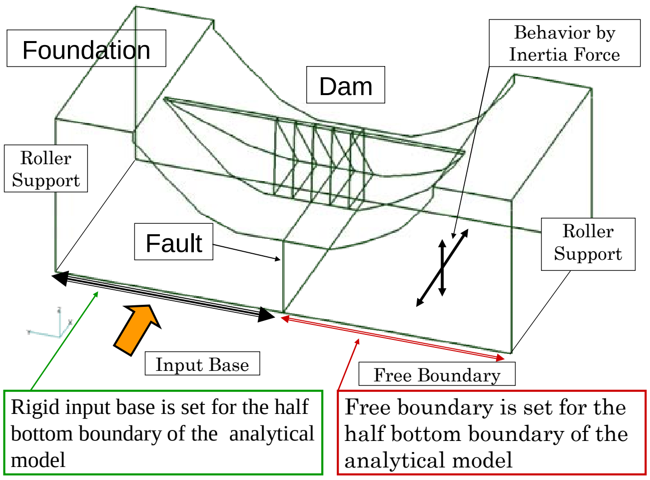


Figure 7 Boundary condition of 3-D analysis model

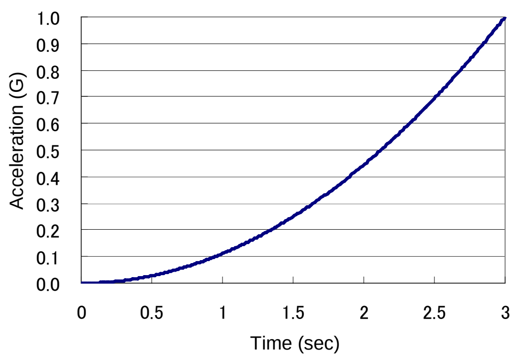


Figure 8 Acceleration wave assumed at the input base
(Input base is the left half of bottom boundary of 3-D model shown in Figure 7.)

2.2.4 Results of case study

The analytical results about the displacement behaviors of dam and fault are shown in Figure 9 and Figure 11. Figure 9 shows the result when the acceleration wave is input in the horizontal up-down stream direction. In this case, the maximum relative displacement of joint elements at the center of dam base was 0.18m. Figure 11 shows the result when the acceleration wave is input in the vertical direction, and the maximum relative displacement of joint elements at the center of dam base was 2.4m. In these cases, the vertical roller support is set at the right side of the joint elements.
Similarly, the analytical results about the time history of relative displacement of joint at the center of dam base are shown in Figure 10 and Figure 12. Figure 10 shows the result when the acceleration wave is input in the horizontal up-down stream direction, and Figure 12 shows the result when the acceleration wave is input in the vertical direction.

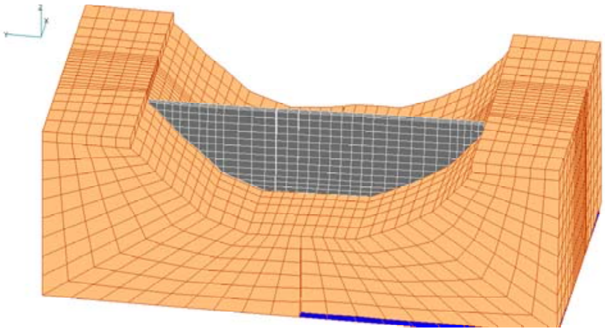
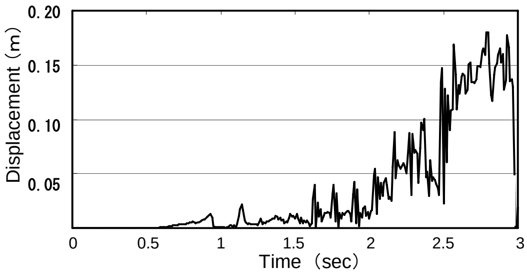


Figure 9 Displacement behavior of dam and fault when the acceleration wave is input in the horizontal stream direction



Case- 1
(**Direction of input wave: Horizontal up-down stream direction**)

Figure 10 Time history of relative displacement of joint at the center of dam base when the acceleration wave is input in the horizontal stream direction

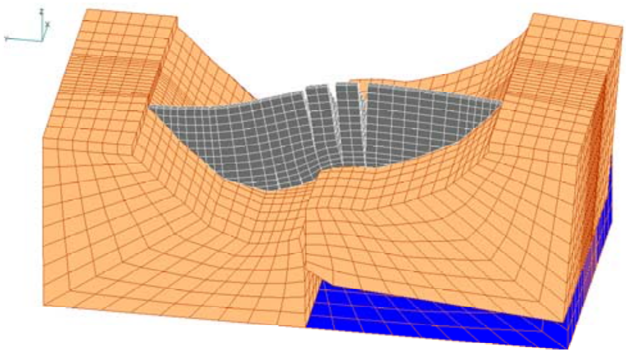
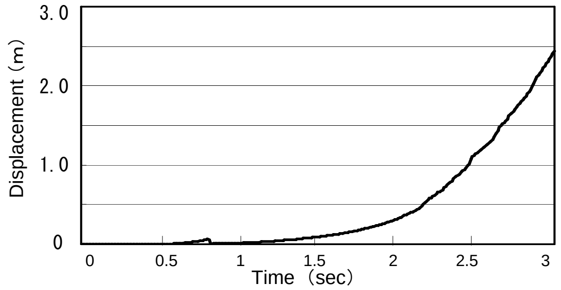


Figure 11 Displacement behavior of dam and fault when the acceleration wave is input in the vertical direction



Case-2
(Direction of input wave: Vertical direction)

Figure 12 Time history of relative displacement of joint at the center of dam base when the acceleration wave is input in the vertical direction

Table 3 Maximum relative displacement at the center of dam base calculated by the 3-D analysis

Analytical case	Maximum relative displacement at the center of dam base
1	0.18 m
2	2.4 m

3. CONSIDERATIONS

Seismic safety evaluation against fault displacement induced by surface earthquake fault is an important subject for dam safety. In order to develop the evaluation method for dam safety against surface earthquake fault, I have devised a 3-D analysis method for evaluating the discontinuous behavior of concrete dam by applying 3-D dynamic analysis method for a coupled dam-joint-foundation-reservoir system.

Applicability of the method proposed was examined by the case study under the assumption that the fault is distributed just below the concrete dam, by taking the actual case of the Shih-Kang Dam damaged by the vertical relative displacement during the 1999 Taiwan Chi-chi Earthquake.

As the results, it is considered that the discontinuous behavior and the residual relative displacement of dam-fault-foundation system can be simulated by the analytical method proposed in this study. It is considered that a vertical fault displacement in connection with a normal fault or a reverse fault can be analyzed by inputting an acceleration wave in the vertical direction from the half of the rigid base of 3-D model, and a horizontal fault displacement in connection with a strike-slip fault can be analyzed by inputting an acceleration wave in the up-down stream direction from the half of the rigid base. By combining a horizontal input and a vertical input, it is considered that the various types of faults can be simulated.

The relative displacements between the contact planes of joint elements at the bottom of dam center will be changed according to the input wave condition and the boundary condition.

A quantitative evaluation method for the dynamic property values of contact plane of fault, the value of damping factor corresponding to the boundary condition, the frequency and the amplitude of input wave, the analytical consideration on the vibration component of the time history of relative displacement of joints, and the verification of validity of the method proposed can be mentioned as the subjects for a future study.

Besides, it is considered that the 3-D dynamic analysis method by applying the progressive wave analysis may be effective for evaluating discontinuous interaction between dam and fault. I will make a study on the 3-D dynamic analysis method by applying the progressive wave analysis as a future study.

4. POSTSCRIPT

Confirmation and securing of safety against the surface earthquake fault is one of the important matters for the long and large structures such as dam, tunnel, railway, highway, bank, etc. It can be concluded that the method proposed is effective for evaluating discontinuous behaviors of the coupled dam and surface earthquake fault system. The proposed method can be broadly applied for various kinds of structure-foundation rock-fault system

It seems that the prediction of earthquake occurrence and the estimation of earthquake motion have been a main theme in the conventional studies on active fault up to now. If it will become possible to predict the movement of surface earthquake fault and to forecast a residual displacement along the surface earthquake fault, it is thought that a rational safety evaluation for the various kinds of ground-structure system will be realized.

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