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SAFETY EVALUATION METHOD FOR CONCRETE DAM AGAINST SURFACE DISPLACEMENT OF EARTHQUAKE FAULT

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ABSTRACT

Several dams were damaged by the surface fault displacements during the 1906 San Francisco Earthquake. The Shih-Kang Dam was destroyed by the surface fault displacement during the 1999 Taiwan Chi-chi Earthquake. From these historical cases, it is considered that the safety evaluation against surface fault displacement is important for the long and large structures. However, the analytical method for evaluating the safety against surface fault displacement is not established thus far. Therefore, I studied on the 3-D analytical method for evaluating the safety of concrete dam against various kinds of surface earthquake fault displacements. Applicability of the proposed method was examined by the case study in regard to the concrete gravity dam.

Introduction

The Upper Crystal Dam (earth-fill, dam height 23m), the Upper Howell Dam (earth-fill, dam height 11m), the Old San Andreas Dam (earth-fill, dam height 8.5m), and so forth were damaged by the surface displacement of the San Andreas Fault during the 1906 San Francisco Earthquake (Sherard, et al. 1974, Leps, et al. 1989). Recently, the Shih-Kang Dam (concrete gravity, dam height 25m) was destroyed by the vertical relative displacement during the 1999 Taiwan Chi-chi Earthquake (Lee, et al. 2002), as shown in Fig. 1.

From these historical cases, it is considered that the safety evaluation against surface fault displacement induced by earthquake fault is important for dams, tunnels, roads, railways, and so forth. And, normal fault, reverse fault, strike-slip fault, rotational fault, and so forth can be supposed in regard to the modes of surface earthquake faults, as shown in Fig. 2. Consequently, it will be necessary to evaluate the safety against various kinds of surface earthquake faults. However, the analytical method for evaluating the safety against relative displacements along the surface earthquake fault has not been practically established yet. So, I studied on the analytical method for simulating the discontinuous behaviors of dams against various modes of surface fault displacements by applying the 3-D dynamic analysis method for the coupled dam-joint-foundation-reservoir system.

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Figure 1. Existing Dam damaged by Surface Fault Displacement

3-D Analytical Method for evaluating Safety against Surface Fault Displacement

Necessity for Study

Some studies on the analytical method in regard to the surface earthquake fault have been made after the 1999 Taiwan Chi-chi Earthquake. 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 Lagrangian particle finite difference method (Konagai, et al. 2001), and so forth were reported for evaluating the deformation of ground and the behavior of structures. But, the analytical method for evaluating the discontinuous behavior of dam-fault-foundation system has not been developed yet. Taking such background into consideration, I studied on the analytical method to evaluate the interaction between dam and surface earthquake fault.

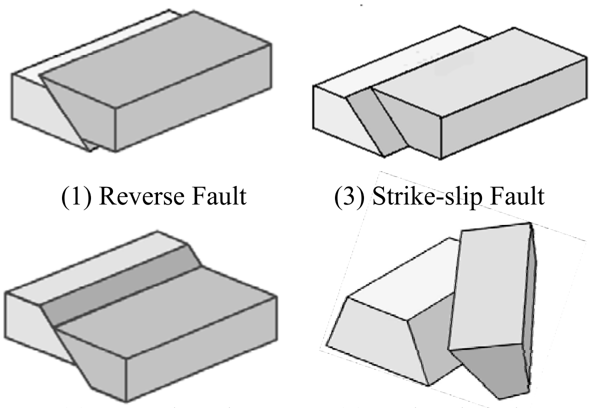
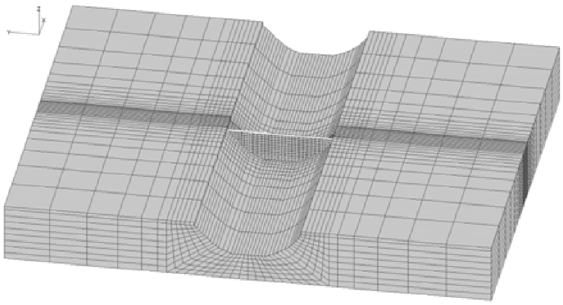


Figure 2. Modes of Faults

3-D Analytical Method proposed

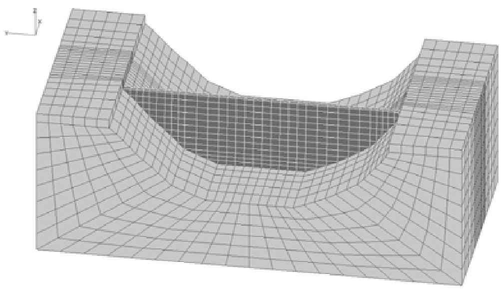
3-D Model for coupled Dam-fault-foundation System

The 3-D dynamic analysis method for the coupled dam-joint-foundation-reservoir system (Ariga, et al. 2000, 2003) was applied for evaluating the interaction between dam and surface earthquake fault by taking the actual phenomena at the Shih-Kang Dam into consideration. In this study, the boundary condition of 3-D analytical model and the method for inputting acceleration wave were contrived. Fig. 3 shows the wide analytical model, which is made by assuming that the surface earthquake fault is distributed just below the dam. The width and the depth of the wide analytical model are 1335m and 1094m, respectively. Fig. 4 shows the narrow analytical model around the dam. The width and the depth of the narrow analytical model are 445m and 218.88m. The dynamic property values of dam and foundation are shown in Table 1. The dynamic property values of dam was identified by the 3-D dynamic simulation analysis for the actual earthquake behavior of the existing concrete dam based on the earthquake motions which were recorded at the 1993 Kushiro-oki Earthquake (Ariga, et al. 2000, 2006, 2007).



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

Figure 3. Wide analytical model



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

Figure 4. Narrow analytical model

Table 1. Dynamic property values of dam and foundation

Items	**Dynamic shear modulus**	**Density**	**Poisson's ratio**	**Damping factor**
Rock foundation	9380 N/mm^2	2.6 t/m^3	0.3	5%
Dam concrete	11032 N/mm^2	2.4 t/m^3	0.2	5%

Modeling of Fault and 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 Fig. 5. These fault and joints are modeled by using the joint elements. The structural and mechanical characteristics of the joint element are shown in Fig. 6 and Fig. 7. In Fig. 5, 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 element-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 joint elements can be set according to the properties of structural materials and the conditions of contact planes.

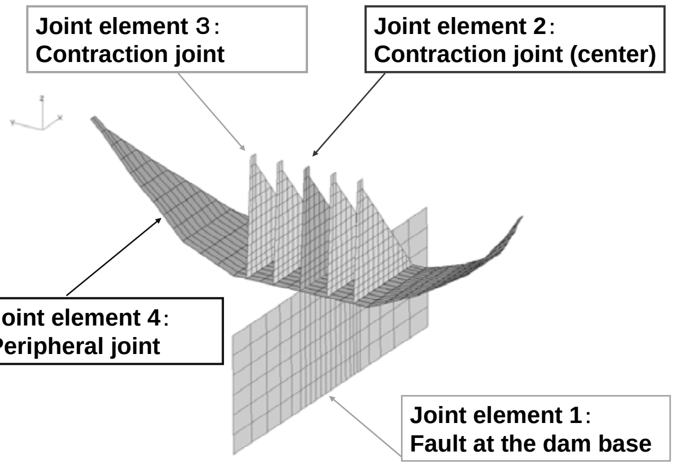


Figure 5. Distribution of fault-contraction joints-peripheral joints

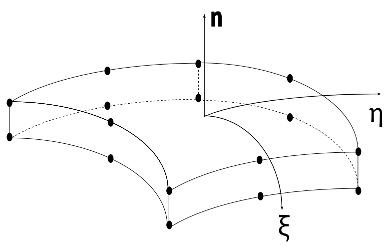


Figure 6. Jjoint element

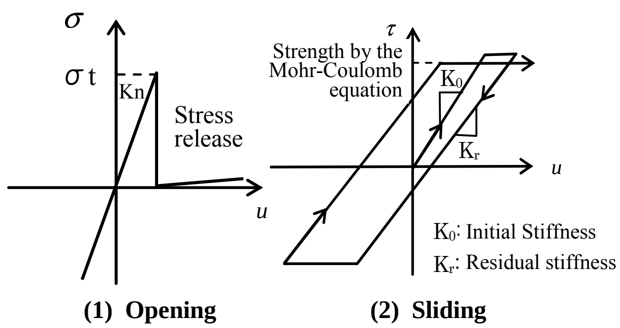


Figure 7. Characteristics of joint element

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

Fault & Joints		Kn N/mm^2	K_0 N/mm^2	C N/mm^2	φ °	Kr N/mm^2	C' N/mm^2	φ` °	Hj %	σt N/mm^2
1	Surface Fault	243000	93000	0	45	1	0	45	5	0.01
2	Contraction Joint(center)	264000	110000	0	45	1	0	45	5	0.01
3	Contraction Joint	264000	110000	0	45	1	0	45	5	0.01
4	Peripheral joint	243000	93000	4.5	45	1	0	45	5	3.00

(No. of Fault & Joints corresponds to Figure 5)

The dynamic property values of the fault, the contraction joints and the peripheral joints 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.

Boundary Condition

Boundary condition of 3-D analytical model is set as shown in Fig. 8. Free boundary is set at the right half of bottom boundary in order to generate a discontinuous displacement along the fault just below the dam center. Acceleration wave is input from the left half of bottom boundary, which is set as the rigid base. The right and left lateral boundaries are set as the roller support in the vertical plane. The front and rear lateral boundaries are set as the free boundary. By setting these boundary conditions, the right half of the 3-D analytical model will move by inertia force, and the discontinuous displacements will occur along the fault. Consequently, the discontinuous behavior of dam against the surface fault displacement, the opening and sliding of the contraction joints and the peripheral joints, and the discontinuous relative displacement can be simulated.

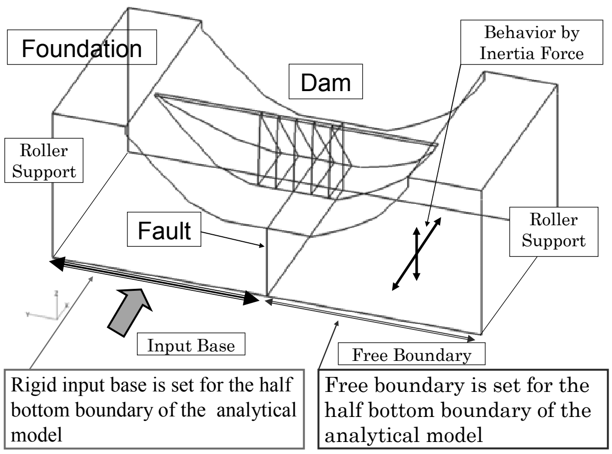


Figure 8. Boundary conditions of 3-D model

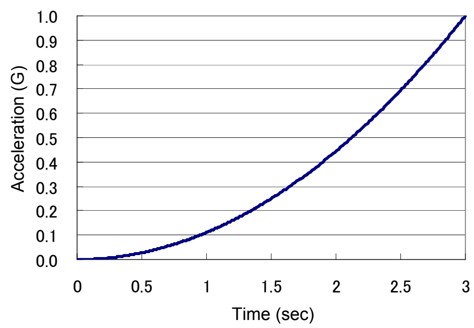


Figure 9. Acceleration wave at input base (Input base is the left half of bottom boundary shown in Figure 8.)

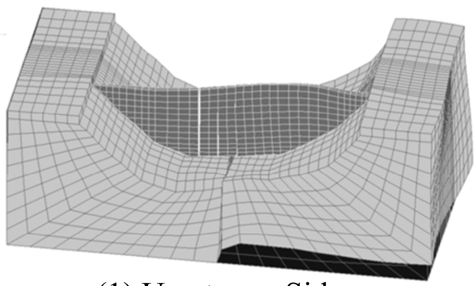
Input Wave

Generally, a normal earthquake motion, whose amplitude starts at 0 gal and ends at 0 gal, is usually used as an input motion in the ordinary dynamic analysis, which is made in order to evaluate the ordinary earthquake response. But, it is difficult to simulate the large-scale discontinuous behavior of coupled dam-fault-joints system by using the normal earthquake motion as the input wave. It is necessary to input very strong acceleration toward one direction in order to simulate the large-scale discontinuous displacements along the fault and joints. For this reason, the acceleration wave shown in Fig. 9 was assumed as the input wave in this study. The acceleration wave can be expressed by the curve of second degree, which is convex down ward. The maximum amplitude of acceleration wave is assumed to be 1G, and the duration time is 3 seconds. This acceleration wave was assumed and used in order to simulate the large-scale discontinuous displacements.

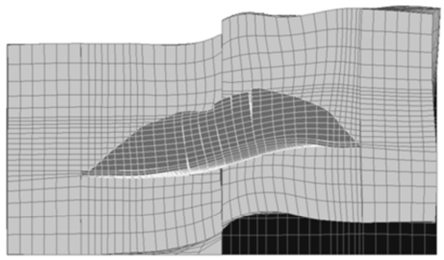
Results of 3-D Analyses

Simulation for Strike-slip Fault

The result of 3-D analysis in regard to the discontinuous behaviors of dam and fault at the time when the acceleration wave was input in the horizontal up-down stream direction by using the wide analytical model is shown in Fig. 10. It is considered that the mode of strike-slip fault can be simulated by inputting the acceleration wave in the horizontal direction. In this case, the maximum relative displacement of joints at the center of dam base was approximately 0.18m.



(1) Up-stream Side



(2) from the above

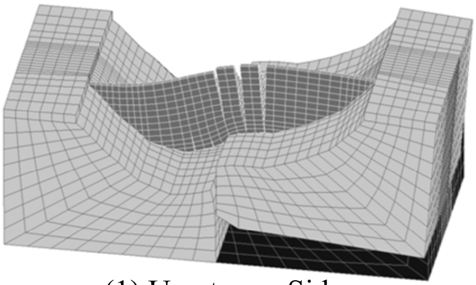
Figure 10. Analytical result for simulating a mode of strike-slip fault
(The acceleration wave was input in the horizontal up-down stream direction.)

Simulation for Reverse Fault or Normal Fault

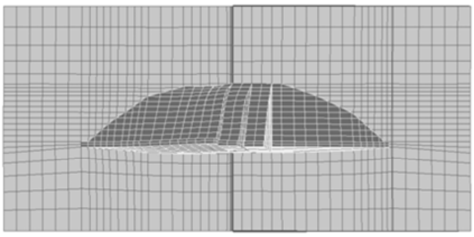
The result regarding the discontinuous behaviors of dam and fault at the time when the acceleration wave was input in the vertical direction by using the wide analytical model is shown in Fig. 11. It is considered that a mode of reverse fault or normal fault can be simulated by inputting the acceleration wave in the vertical direction. In this case, the maximum relative displacement of joints at the center of dam base was approximately 2.4m.

Simulation for Mode of Rotational Fault

Fig.12 shows the result when the acceleration wave is input in the vertical direction by using the narrow analytical model is shown in Fig. 12. A mode of rotational fault can be simulated by inputting the acceleration wave in the horizontal direction and using the narrow model. In this case, the maximum relative displacement of joints at the center of dam base was approximately 1.9m.

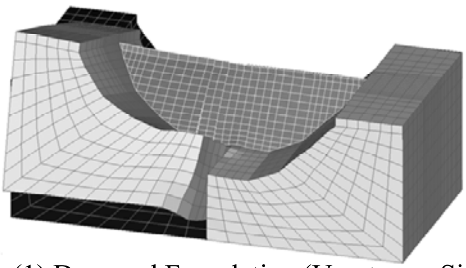


(1) Up-stream Side

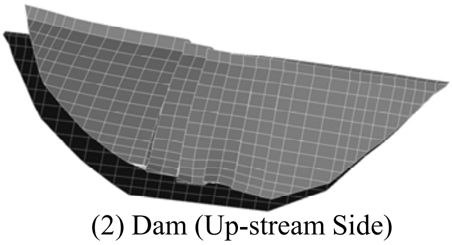


(2) from the above

Figure 11. Analytical result for simulating a mode of reverse fault
(The acceleration wave was input in the vertical direction.)



(1) Dam and Foundation (Up-stream Side)



(2) Dam (Up-stream Side)

Figure 12. Analytical result for simulating rotational fault
(The acceleration wave was input in the horizontal direction of the narrow analytical model.)

Conclusions

Confirmation and securing of safety against surface earthquake fault is an important subject for the long and large structures such as dams, tunnels, railways, highways, banks, etc.

Seismic safety evaluation method against surface displacement induced by earthquake fault has not been practically established yet. So, I have devised a 3-D analysis method for evaluating the safety of dams against surface earthquake fault by applying 3-D dynamic analysis method for a coupled dam-joint-foundation-reservoir system.

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

As the results, it is considered that the discontinuous behavior and the residual relative displacement of dam-joints-fault-foundation system can be simulated by the method proposed.

It is considered that the vertical fault displacement in connection with the reverse fault can be simulated by inputting the acceleration wave in the vertical direction from the half of the rigid base of the 3-D model. And the horizontal fault displacement in connection with the strike-slip fault can be analyzed by inputting the acceleration wave in the horizontal up-down stream direction. By combining the horizontal input and the vertical input, it is considered that the various types of faults, such as rotational fault, can be simulated.

The relative displacements along the fault and joints will be changed according to the conditions of the input wave and the boundary of analytical model. It is considered that the quantitative evaluation for dynamic property values of contact plane of fault and joints, the frequency and the amplitude of input wave, and the verification of validity of the method proposed are the subjects for future study.

It can be concluded that the method proposed will be 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-fault system

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

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