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Study on Earthquake-Induced Permanent Deformation of Earth-Rockfill Dams

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STUDY ON EARTHQUAKE-INDUCED PERMANENT DEFORMATION OF EARTH-ROCKFILL DAMS

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ABSTRACT

Based on the experimental data, a three-dimensional (3-D) nonlinear effective stress seismic response analysis method of earth-rockfill dams is proposed with the dissipation and diffusion of seismic pore-water pressure been considered. Then a method for evaluating the earthquake-induced permanent deformation of earth-rockfill dams taking into account both residual shear strain and residual volumetric strain is presented. The method proposed by Taniguchi is adopted to evaluate the earthquake-induced permanent deformation caused by residual shear strain. In order to evaluate the earthquake-induced permanent deformation caused by residual volumetric strain, the saturated part and the non-saturated part of the dams are treated separately. An expression of residual volumetric strain for non-saturated soils is proposed by analyzing the test data. As an example, the evaluation of the earthquake-induced permanent deformation of Zipingpu dam is performed.

INTRODUCTION

Prediction of earthquake-induced permanent deformation of earth-rockfill dams is of great importance in design and seismic safety assessment. There are essentially two different ways of approach. The first one is so-called Sliding Block Analysis Method originally proposed by Newmark (1965) and modified by Makdisi and Seed (1978). It considers the permanent deformation as a cumulation of a number of intermittent displacements of the sliding portion relative to the intact portion of the earth-rockfill dams caused by strong shocks of the earthquake. The second one is so-called Integral Continuum Analysis Method originally suggested by Serff and Seed (1976). It considers the earth-rockfill dams as deformable continuum and utilizes the so-called strain potential obtained from cyclic tests of soil samples into the analysis of the earthquake-induced permanent deformation through various ways.

At present, most methods only calculate the earthquake-induced permanent deformation caused by residual shear strain. In fact, the residual volumetric strain of earth-rockfill material can have great influence on the permanent deformation, so the permanent deformation caused by residual volumetric strain should be take into account. In recent years, There're many dynamic experiments of earth-rockfill material have been performed in IWHR with lots of experimental data collected. Based on the previous research work (Wang Wen-shao, *et al* 1987, Zhao Jian-ming *et al.* 1997, etc.) and the aforementioned experimental data, a method to evaluate the earthquake-induced permanent deformation of earth-rockfill dams taking into account both residual shear strain and residual volumetric strain is presented.

THREE-DIMENSIONAL (3-D) NONLINEAR EFFECTIVE STRESS SEISMIC RESPONSE ANALYSIS METHOD OF EARTH-ROCKFILL DAMS

Dynamic Constitutive Model

The nonlinear hysteretic stress-strain behavior of the dam materials is modeled by using equivalent nonlinear viscoelastic model. According to the large-scale dynamic triaxial tests performed in IWHR, the relationship of shear modulus and damping ratio versus shear strain can be obtained. After normalized by reference strain γ_r, the relationship curves are as seen in Fig. 1, in which G = shear modulus, γ = shear strain, λ = damping ratio, G_{max} = maximum shear modulus. G_{max} can be computed by the following relationship:

$$G_{max} = K_1\left(\sigma_0'\right)^{m_1} \quad (\mathrm{MPa}) \qquad (1)$$

in which K_1 and m_1 are parameters determined by tests, σ_0' = the mean effective principal stress, in MPa.

Calculation of Increasing Seismic Pore-water Pressure

It is very import to calculate the seismic pore-water pressure

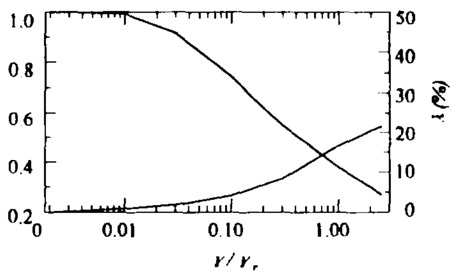

Fig. 1. $G/G_{max} \sim \gamma/\gamma_r$ and $\lambda \sim \gamma/\gamma_r$ Relationship

appropriately in effective stress seismic response analysis and liquefaction potential assessment of earth-rockfill dams. There 're several methods proposed to predict the generation of seismic pore-water pressure. In fact, the generation of seismic pore-water pressure is very complicated. It's very difficult to express the mechanism exactly by using some certain parameters, for there are so many uncertain contributing factors. In this paper, one method utilizing the experimental curves directly has been employed to predict the generation of seismic pore-water pressure. The typical curves obtained from dynamic triaxial test data can fully express the relationship between dynamic pore-water pressure ratio P_d / σ_0' and dynamic shear stress ratio τ_d / σ_0', as shown in Fig. 2.

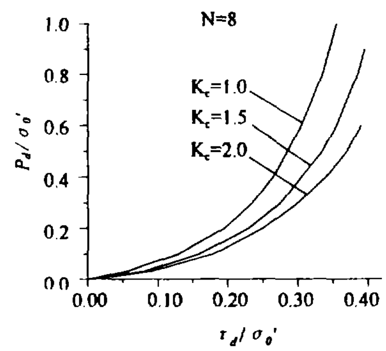

Fig. 2. Relationship between dynamic pore-water pressure ratio and dynamic shear stress ratio

in which P_d = seismic pore-water pressure, $\tau_d = 0.65\,\tau_{max}$, τ_{max} =maximum dynamic shear stress during all previous time intervals. K_c = consolidation ratio. The equivalent number of cycles N can be determined by using the relationship between equivalent number of cycles, earthquake magnitude and strong shock time. The equivalent number of cycles should be distributed to each calculating time interval according to the acceleration distribution.

FEM Equation of Motion Considering Dissipation and Diffusion of Seismic Pore-water Pressure

Based on the conceptions of Nodal Equivalent Volume and 3-D Nodal Equivalent Flow proposed by the authors, a 3-D nonlinear effective stress seismic response analysis method considering the dissipation and diffusion of seismic pore-water pressure by applying Biot consolidation theory is presented.

Dynamic FEM Equation. The dynamic FEM equation of dams can be expressed as:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{R_t\} \tag{2}$$

in which $\{U\}$, $\{\ddot{U}\}$ and $\{\dot{U}\}$ = the nodal point displacement, acceleration and velocity vectors; [M], [C] and [K] = the mass, damping and stiffness matrices; and $\{R_t\}$ = load vectors.

Nodal Equivalent Volume and 3-D Nodal Equivalent Flow. Fig. 3 is a mini element dv=dxdydz, the Nodal Equivalent Volume of node i is defined as dv_i=dxdydzN_i , as shown by the shadow part in Fig. 3, in which N_i is shape function.

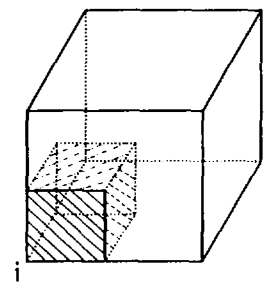

Fig. 3. Sketch map of Nodal Equivalent Volume

Fig. 4 shows a mini seepage element. The equivalent flow in unit time of node i passing through the nodal equivalent volume dv_i in x direction is:

$$d(\Delta Q_{ix}) = q_x N_{i,x}\, dxdydz \tag{3}$$

In a similar way, the equivalent flows in y and z directions can be obtained. Then by integral operation, the 3-D equivalent flow in unit time of node i can be determined as follows:

$$\begin{aligned}\Delta Q_i &= \Delta Q_{ix} + \Delta Q_{iy} + \Delta Q_{iz} \\ &= \iiint \left[\frac{\partial N_i}{\partial x} \quad \frac{\partial N_i}{\partial y} \quad \frac{\partial N_i}{\partial z} \right] \{q\}\, dxdydz \\ &= -\frac{1}{\gamma_w} \iiint [N]^T [L][K][L]^T [N]\, dxdydz\ \{p_i\}\end{aligned} \tag{4}$$

where

$$[L] = \left[\frac{\partial}{\partial x} \quad \frac{\partial}{\partial y} \quad \frac{\partial}{\partial z} \right]$$

$$[K] = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix}$$

$$\{q\} = -\frac{1}{\gamma_w} [K][L]^T p$$

If define $[k_q]$ as:

$$[k_q] = \frac{1}{\gamma_w} \iiint [N]^T [L][K][L]^T [N]\, dxdydz$$

then:

$$\{\Delta Q\}^e = -[k_q]\{p\}^e \tag{5}$$

in which k_x , k_y and k_z = the coefficients of permeability in x, y and z directions respectively; γ_w =unit weight of water; q_x , q_y and q_z = velocities of flow in x, y and z directions respectively.

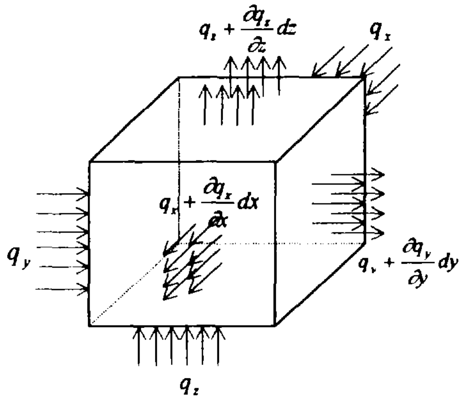

Fig. 4. Mini seepage element

FEM Expression of Biot Consolidation Equation. By applying the conceptions of the nodal equivalent volume and 3-D nodal equivalent flow mentioned above into the equilibrium equation and continuity equation of Biot consolidation theory, the FEM expression of Biot consolidation equation can be deduced as follows:

$$\begin{bmatrix} [K_s] & [K_p] \\ [K_p]^T & -\frac{1}{2}[K_q] \end{bmatrix} \begin{Bmatrix} \Delta\delta \\ \Delta p_t \end{Bmatrix} = \begin{Bmatrix} \{\Delta F\} - \{\Delta F'\} \\ \Delta t[K_q]\{p_{t-\Delta t}\} \end{Bmatrix} \tag{6}$$

The arithmetic techniques including direct time integration (Wilson- θ method) and iterations at each time step have been employed in the calculation procedure with eight-node isoparametric brick elements used. The details of solution technique and the formulation of the system matrices are available in Ref.(Zhao Jian-ming, 1997).

EVALUATION OF THE EARTHQUAKE-INDUCED PERMANENT DEFORMATION

On the basis of above proposed seismic response analysis method, a method to evaluate the earthquake-induced permanent deformation of earth-rockfill dams taking into account both residual shear strain and residual volumetric strain is presented.

Evaluation of the Earthquake-Induced Permanent deformation Caused by Residual Shear Strain

In order to evaluate the earthquake-induced permanent deformation caused by residual shear strain, the method proposed by Taniguchi, *et al* (1983) is adopted.

According to the cyclic triaxial tests, the relationship between normalized shear stress q/p_0' and residual shear strain γ can be expressed as:

$$\frac{q}{p_0'} = \frac{\gamma}{a + b\gamma} + \frac{q_0}{p_0'} \tag{7}$$

in which $q = q_s + q_d$, q_s =static shear stress, q_d =dynamic shear stress, p_0' = static effective mean stress, a, b = constants depend on number of cycles, effective lateral confining stress and effective consolidation ratio, etc.

There are three forces should be applied to dam, i. e. gravity force, water pressure caused by reservoir and earthquake force. About the earthquake force, the equivalent nodal force can be determined by $F_e = ma_e$, in which m = mass of element, a_e = equivalent acceleration. According to Taniguchi's advice (1983) , the equivalent force should be applied first in downstream direction and then in upstream direction. And the resulting deformations are superimposed to determine the permanent deformation. Iterative method is used to get the appropriate shear modulus for each element according to above relationship.

Evaluation of the Earthquake-Induced Permanent deformation Caused by Residual Volumetric Strain

In order to evaluate the earthquake-induced permanent deformation caused by residual volumetric strain, the saturated part and the non-saturated part of the dam are treated separately.

Saturated Part. For the saturated part of the dam, the permanent residual volumetric deformation is due to the dissipation of seismic pore-water pressure, so it can be calculated directly in the effective stress seismic response analysis process by using above proposed 3-D seismic response analysis method which has considered the dissipation and diffusion of seismic pore-water pressure by Biot consolidation theory. In the procedure, step-by-step time integration method (Wilson- θ method), high efficiency iteration and other numerical techniques are used.

Non-saturated Part. For the non-saturated part of the dam, the dynamic triaxial tests of non-saturated earth-rockfill material have been performed by IWHR (Wang Kun-yao *et al*, 1998). The volumetric changes of the non-saturated samples have been measured correctly during tests. Fig. 5 and Fig. 6 show part of the test results. By analyzing the test data, the relationship between residual volumetric strain and dynamic stress is obtained and the expression of residual volumetric strain is proposed as follows:

$$\varepsilon_{dV} = K_V (\Delta\tau / \sigma_0')^{n_V} \tag{8}$$

in which ε_{dV} = residual volumetric strain (%) , $\Delta\tau/\sigma_0'$ = dynamic shear stress ratio, $\Delta\tau$ = dynamic shear stress, σ_0' =mean effective principal stress, K_V , n_V = parameters varied with σ_3' , K_c and N, as shown in table 1. σ_3' = effective lateral confining stress, K_c = effective consolidation ratio, N = number of cycles.

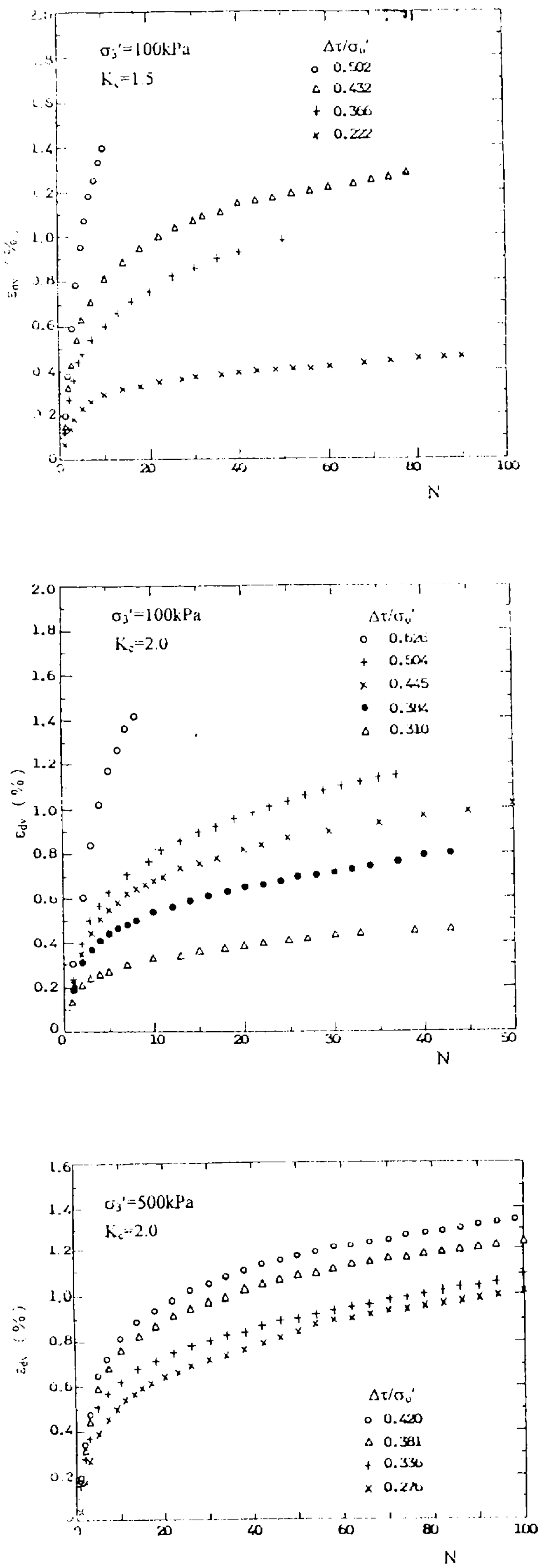

Fig. 5. Relationship between ε_{dv} and N

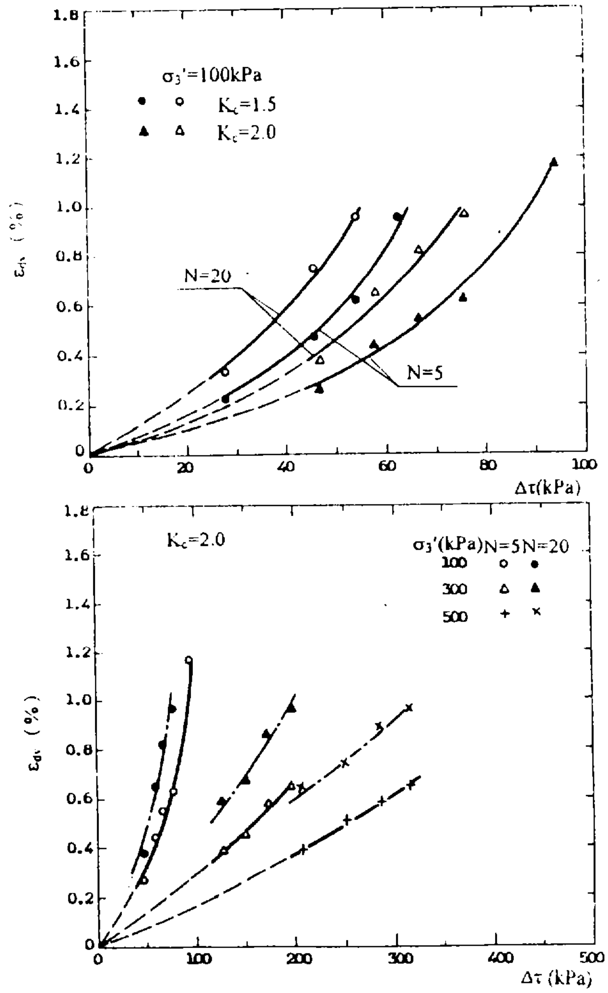

Fig. 6. Relationship between ε_{dv} and $\Delta\tau / \sigma_0'$

Table 1. Parameters K_V and n_V in express (8)

σ_3' (kPa)	K_c	N	K_V	n_V
100	1.5	5	3.008	1.770
		10	3.682	1.754
		20	3.895	1.642
		30	4.264	1.624
	2.0	5	2.506	1.889
		10	2.842	1.771
		20	3.546	1.842
		30	3.757	1.772
300	2.0	5	1.960	1.294
		10	2.445	1.267
		20	2.772	1.240
		30	2.973	1.225
500	2.0	5	1.814	1.161
		10	2.257	1.146
		20	2.518	1.084
		30	2.749	1.084

The residual volumetric strain ε_{dV} calculated by expression (8) should be taken as residual strain potential, so the equivalent node force method is applied to calculate the permanent deformation due to residual volumetric strain.

After such strain potential of element be transformed to the strain potential $\{\varepsilon_p\}$ in Cartesian coordinate system, the equivalent nodal force can be calculated by following expression:

$$\{F_p\} = \iint_V [B]^T [D] \{\varepsilon_p\} dV \qquad (9)$$

Applying above equivalent nodal force on dam, the permanent deformation caused by residual volumetric strain can be evaluated.

3-D SEISMIC RESPONSE ANALYSIS OF ZIPINGPU DAM

Zipingpu Dam and Finite Element Mesh

Zipingpu dam is a concrete faced rockfill dam being built in Sichuan province of China. The dam is 156 m high above its lowest foundation. The crest has a width of 30 m and a maximum length of 638 m. Upstream and. Downstream slopes are at 1.4:1 and 1.5:1 respectively.

The 3-D finite element mesh consists of 2536 nodes and 1944 elements. Fig. 7 shows the finite element mesh of the maximum cross section of the dam.

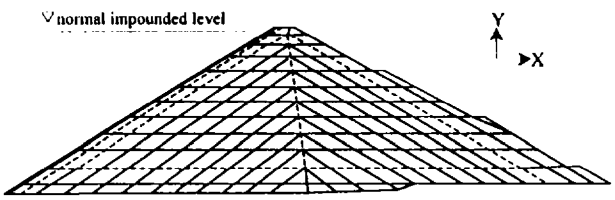

Fig.7. Finite element mesh of maximum cross section

Input Ground Motion

It's very important to select proper input ground motion in seismic response analysis of dams. According to the seismicity analysis of Zipingpu dam area, the input acceleration time history of Zipingpu dam is synthesized, as shown in Fig. 8. It is 20 sec long with a peak acceleration of 0.26 g and a predominant period of 0.17 sec and input in the upstream-downstream direction.

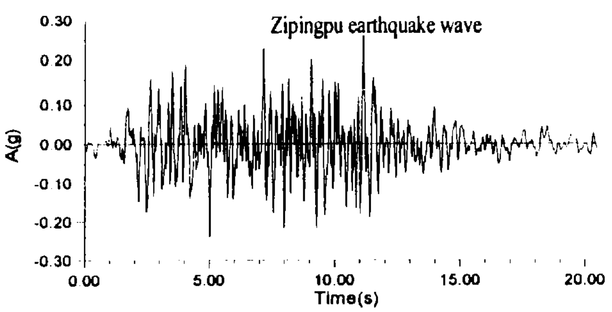

Fig.8. Input ground motion

Seismic Response Analysis

Static FEM analysis is performed applying Duncan E-B model. Then the seismic response of Zipingpu dam at normal impounded level is analyzed by above proposed 3-D nonlinear effective stress seismic response analysis method. Some relative calculation results are listed as follows.

Fig. 9 shows the crest acceleration time history in upstream-downstream direction. The maximum crest acceleration is 0.79 g. The maximum acceleration contours and the maximum dynamic shear stress (τ_{yx}) contours of maximum cross section are shown in Fig. 10 and Fig. 11 respectively.

The generation, dissipation and diffusion of seismic pore-water pressures in the saturated part of dam have been evaluated. Fig. 12 shows the time histories of maximum pore-water pressure ratio in the bottom of dam. u/σ_m = pore-water pressure ratio, in which u = pore-water pressure, σ_m = mean principal stress. The maximum pore-water pressure ratio of curve a and curve b are 0.462 and 0.051 respectively, so there's no probability of liquefaction during earthquake.

The calculation results show the dam have good seismic stability. The minimum factor of safety is 1.87.

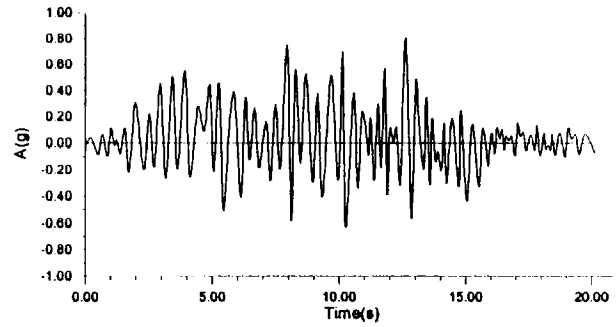

Fig.9. Crest acceleration time history

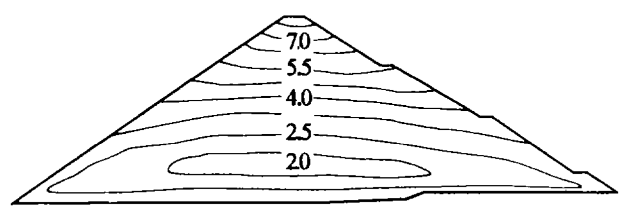

Fig.10. Contours of maximum acceleration (m/s²)

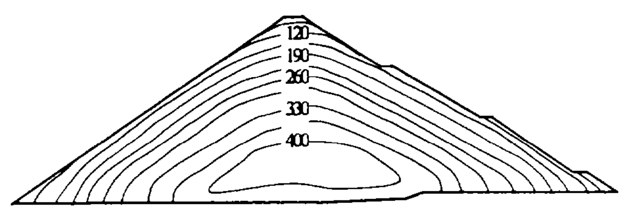

Fig.11. Contours of dynamic shear stress (kPa)

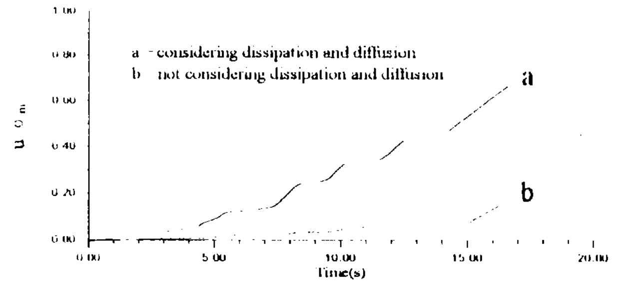

Fig. 12. Time history of maximum pore-water pressure ratio

Earthquake-Induced Permanent Deformation

The earthquake-induced permanent deformation of Zipingpu dam is evaluated by using above proposed method. The parameters for calculation are determined by test results including table 1 as reference.

Fig. 13 and 14 show the earthquake-induced permanent deformation contours of maximum cross section in upstream-downstream direction and vertical direction respectively. The skeleton map of permanent deformation is shown in Fig. 15. The maximum values in upstream-downstream direction and vertical direction are 13.63 cm and 18.14 cm respectively. The location of the maximum deformation is on the crest of dam. The permanent deformations of downstream slope are bigger than the permanent deformations of upstream slope partly due to concrete slab 's function.

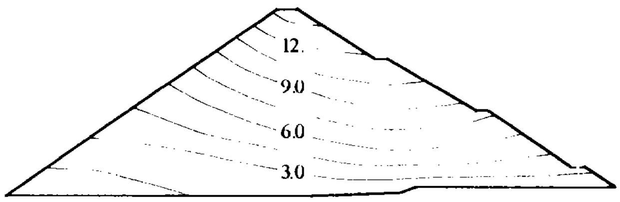

Fig. 13. Contours of permanent deformation in upstream-downstream direction (cm)

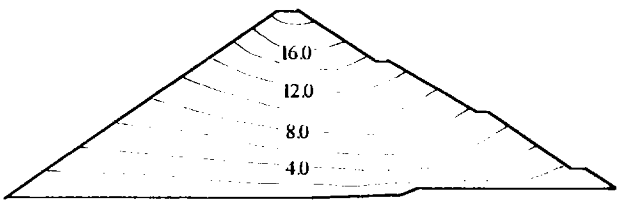

Fig. 14. Contours of permanent deformation in vertical direction (cm)

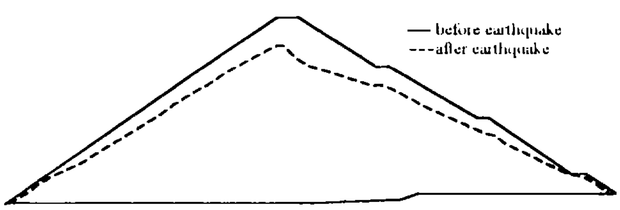

Fig. 15. Skeleton map of permanent deformation

CONCLUSIONS

Based on the experimental data, a three-dimensional (3-D) nonlinear effective stress seismic response analysis method of earth-rockfill dams is proposed. In the proposed method not only the generation but also the dissipation and diffusion of seismic pore-water pressure can be considered.

The presented method to evaluate the earthquake-induced permanent deformation of earth-rockfill dams can evaluate the permanent deformation caused by both residual shear strain and residual volumetric strain. An expression of residual volumetric strain for non-saturated soils is proposed by analyzing the test data.

The seismic response analysis of Zipingpu dam is performed by applying proposed method. The results including earthquake-induced permanent deformation and assessment of liquefaction potential of the dam show the proposed method and program are feasible and practical.

ACKNOWLEDGMENT

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