SEISMIC CRACKING AND STRENGTHENING OF CONCRETE GRAVITY DAMS

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SUMMARY

Concrete gravity dams designed in compliance with the present specification are likely to experience cracking under intense shaking like maximum credible earthquakes. Dangerous cracking in dam body should be prevented in advance to ensure the serviceability of dams. In this paper, the safety of concrete gravity dams under strong ground motions is investigated. First, the dam response during earthquakes is simulated by the FE-BE method, including the dam-foundation-reservoir interaction. The nonlinear tensile behavior of concrete is represented by the smeared crack model to predict the possible earthquake-induced cracking in the dam body. Then some measures to prevent the cracking of dam body are presented. The measures are, for example, adjustment of dam section, local reinforcement and post-tension technique. The adjustment of dam section will reduce the tensile stress in dam body and avoid the occurrence of cracking. Local reinforcement at possible cracking positions is expected to resist the propagation of cracks and reduce the damage of dam body, although it might not prevent the initial cracking. Post-tension technique exerts pre-compressive stress in dams to offset the tensile stress during earthquakes. Effects of these measures are evaluated by numerical simulation. It is shown that these measures could improve the cracking-resistant behavior of concrete gravity dams effectively.

INTRODUCTION

Concrete dams should be designed to resist two levels of earthquakes: level one is design base earthquake and level two is maximum credible earthquake. Although there have been only a few examples of earthquake-induced damage in concrete dams [Hall, 1988], this fact could not give us the confidence regarding the safety of concrete dams since concrete dams have rarely experienced intensive earthquake excitations. The tremendous damage caused by the 1995 Hyogoken-nanbu earthquake demonstrated that the earthquake resistance of structures designed in compliance with the present specification is insufficient under near-field earthquakes, so the dam safety under intensive excitations must be evaluated carefully.

Because concrete cannot sustain highly tensile stress, concrete gravity dams are likely to experience cracking during large earthquakes. Once cracking occurs, it will propagate deeply inside the dam body. Even though cracks in dam body do not imply the failure of dam immediately, they represent the defects that alter the structural resistance and may lead to failure of dam body. So the cracking of concrete is an important factor in the safety evaluation of gravity dams and any development of cracking in dam body should be prevented in advance to ensure the dam safety under large earthquakes.

This study deals with the cracking and strengthening of concrete gravity dams under strong ground motions. First, The possible earthquake-induced cracking in concrete gravity dams is investigated by using the smeared crack model. Then, some possible measures to prevent the cracking of dam body are suggested. These measures are, for example, adjustment of dam section, local reinforcement and post-tension technique. A concrete gravity dam designed in compliance with the present specification is taken as an example and the effect of strengthening measures is checked by numerical examples.

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The Nonlinear FE-BE Method

As the finite element method is ideal for the analysis of material inhomogeneity and the boundary element method is suitable for the analysis of infinite domain, they are coupled in this study to analyze the seismic cracking of concrete gravity dams including the dam-foundation interaction. The dam body is discretized by finite elements and the foundation is discretized by boundary elements.

The dynamic equation for the finite element region can be expressed as

$$[M_d]\{\Delta\ddot{u}\}+[C_d]\{\Delta\dot{u}\}+[K_d]\{\Delta u\}=\{\Delta P_{df}\} \tag{1}$$

in which $[M_d]$ and $[K_d]$ are the mass and stiffness matrices; $[C_d]$ is the Rayleigh damping matrix, which is a linear combination of the mass and stiffness matrices; $\{\Delta P_{df}\}$ is the incremental vector of nodal force representing the interaction between dam and foundation.

The discretized form of the boundary integral equation can be written as [Touhei and Ohmachi, 1993]

$$[H_f]_1\{u\}_N=[G_f]_1\{\sigma\}_N-\sum_{n=1}^{N-1}\left([H_f]_{N-n+1}\{u\}_n-[G_f]_{N-n+1}\{\sigma\}_n\right)+\{f\}_N \tag{2}$$

where $[H_f]$ and $[G_f]$ are the influence coefficient matrices obtained from Green's functions for traction and displacement. The vector $\{f\}_N$ is determined by free-field ground motion and initial conditions. Solving equation (2) for the traction vector at the N-th time step leads to the following time marching scheme:

$$\{\sigma\}_N=[k_f]\{u\}_N-\{F\}_N \tag{3}$$

The traction vector can be transformed into a nodal vector as

$$\{P_{fd}\}_N=[D_f]\{\sigma\}_N=[K_f]\{u\}_N-[D_f]\{F\}_N \tag{4}$$

where $[D_f]$ is the distribution matrix determined from spatial interpolation functions for $\{u\}$ and $\{\sigma\}$; $\{P_{fd}\}_N$ is the vector of nodal force representing the interaction between foundation and dam. Equation (4) can be written in the incremental form as

$$\{\Delta P_{fd}\}=[K_f]\{\Delta u\}-[D_f]\{\Delta F\} \tag{5}$$

At dam-foundation interface, the equilibrium of nodal force can be expressed as

$$\{\Delta P_{df}\}+\{\Delta P_{fd}\}=0 \tag{6}$$

Substituting (1) and (5) into (6), we have

$$[M_d]\{\Delta\ddot{u}\}+[C_d]\{\Delta\dot{u}\}+([K_d]+[K_f])\{\Delta u\}=[D_f]\{\Delta F\} \tag{7}$$

This is the coupled FE-BE equation and it can be combined with any nonlinear material model in the finite element region.

Equation (7) can be solved by the Newmark β -method. According to this method, equation (7) is rewritten as

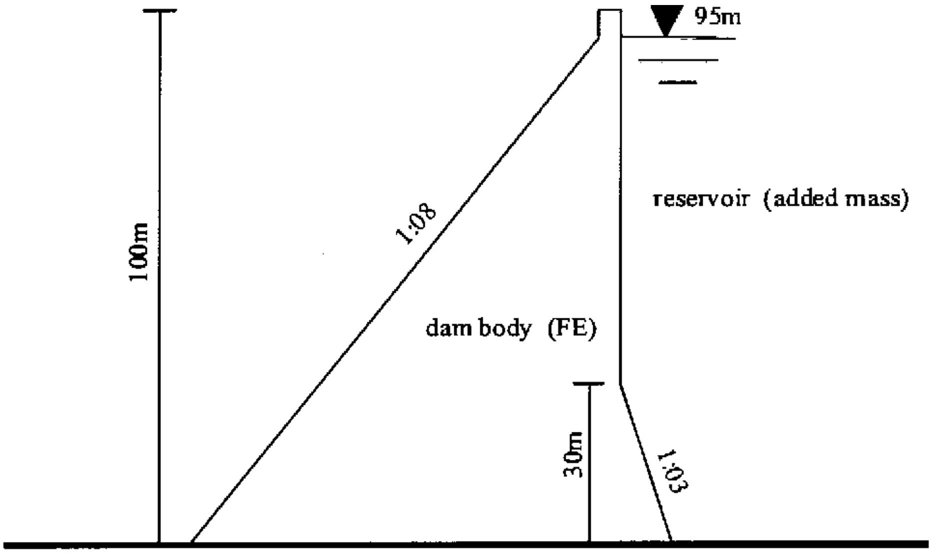
$$\left(\frac{1}{\beta\Delta t^2}[M_d]+\frac{\delta}{\beta\Delta t}[C_d]+[K_d]+[K_f]\right)\{\Delta u\}=$$
$$[D_f]\{\Delta F\}+\left(\frac{1}{2\beta}[M_d]+\frac{\delta-2\beta}{2\beta}[C_d]\Delta t\right)\{\ddot{u}\}_t+\left(\frac{1}{\beta\Delta t}[M_d]+\frac{\delta}{\beta}[C_d]\right)\{\dot{u}\}_t \tag{8}$$

where Δt is a time interval, δ and β are integration parameters and the subscript t denotes a time step.

The nonlinear tensile behavior of concrete is represented by the smeared crack model [Zhang and Ohmachi, 1998]. The initiation and propagation of cracking are based on the strength criterion. The principal stress of an element is checked in terms of a bilinear failure criterion. If the failure criterion is met, cracking takes place over the element in the direction normal to the maximum principal stress. After cracking, the stiffness of the concrete normal to the crack plane is reduced to zero and the concrete model becomes orthotropic. When the strain normal to the crack plane is less than zero, the crack is considered to become closing and the concrete recovers its original stiffness in the direction normal to crack plane without the tensile strength recovered. Any tensile stress normal to the closed crack will bring about reopening of the crack.

SYSTEM ANALYZED

2 dimensional dam-foundation-reservoir system is supposed to analyze cracking of concrete gravity dams under large earthquakes. The dam height is 100m and the shape is designed in compliance with the present specification. The foundation is hard granite. The water lever is 95m. The self-weight of dam and hydrostatic pressure are applied to the dam body as the initial loads. Hydrodynamic pressure on the upstream face of dam body during earthquakes is represented by added mass according to Westergaad's formula. The analyzed system is shown in Figure 1.



foundation (BE)

Figure 1. System analyzed

The material properties of dam concrete and foundation are listed in Table 1. For dynamic calculation, the elastic modulus, strength and fracture energy of concrete are increased by 10% to account approximately for the strain rate effect.

Table 1. Material properties

	dam	foundation
Elastic modulus E	25000MPa	33200MPa
Poisson ratio	0.2	0.2
Density	2400kg/m^3	2700kg/m^3
Compressive strength f_c	20.0MPa	-
Tensile strength f_t	2.0MPa	-
Fracture energy G_f	250N/m	-
Damping ratio	0.05	-

SEISMIC RESPONSE OF DAM BODY

To ensure the fracture energy conservation of concrete in the cracking analysis, the characteristic size of finite elements h_c is related with the properties of concrete. For the elasto-brittle crack model, the relation is

$$h_c = \frac{2EG_f}{f_t^2} \tag{9}$$

Equation (9) will be used to determine the mesh size of finite elements.

The Pacoima dam basement record in the 1994 Northridge earthquake, which has a maximum acceleration of 430cm/s^2, is integrated twice as the input ground motion in this study, as shown in Figure 2. This record containing characteristics of dam site seems appropriate for the present analysis.

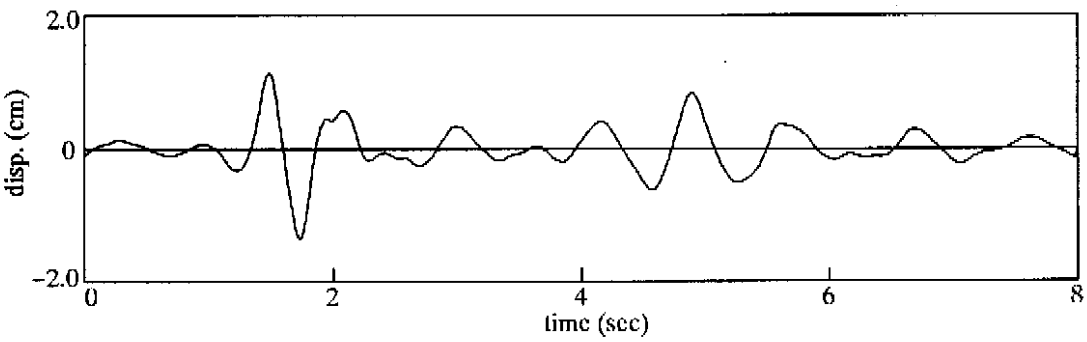


Figure 2. Input ground motion

Under the intensive excitation as shown in Figure 2, cracking occurs in the dam body. The displacement response at dam crest is shown in Figure 3. Cracking state of dam body at several selected times is shown in Figure 4, in which the cracked elements are represented by dots at the element centers. According to the calculation results, cracking initiates at the dam heel at 1.66s and propagates along the dam base. At 1.77s, new cracking occurs at the discontinuity of upstream face and propagates in the horizontal direction. The cracking propagation in the dam body stops at 1.81s.

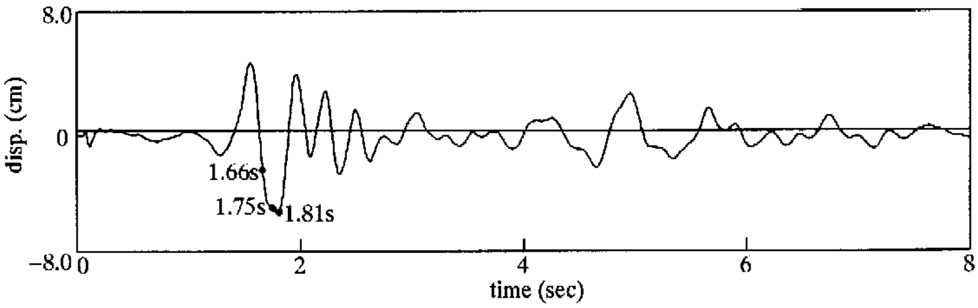


Figure 3. Response of dam crest

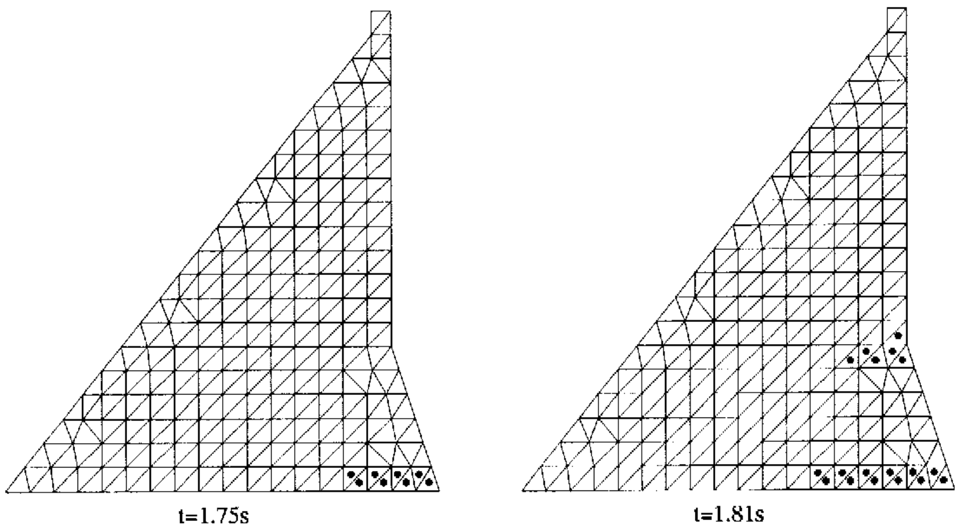


Figure 4. Cracking of dam body

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SEISMIC STRENGTHENING OF CONCRETE GRAVITY DAMS

Especially after the 1995 Hyogoken-nanbu earthquake, the safety of concrete gravity dams under near-field earthquakes is a matter of concern in Japan. This is partly because concrete gravity dams designed in compliance with the present specification will experience tensile stress under near-field earthquakes and partly because the tensile stress might cause severe cracking of dam body. Hence, practical measures must be adopted to ensure the safety of dam body under near-field earthquakes.

ADJUSTMENT OF DAM SECTION

During earthquakes, tensile stress in the dam body is caused by water pressure on the upstream face and inertia force of dam body. These forces are not only dependent on the ground motion but also dependent on the profile of the dam. For example, hydrostatic pressure depends on the gradient of upstream face. For vertical upstream face, the hydrostatic pressure is horizontal and most unfavorable. Inclined upstream face can reduce the hydrostatic pressure in the horizontal direction and the vertical component of hydrostatic pressure on the inclined upstream face is favorable to the safety of dam body. On the other hand, sudden slope change of dam face will lead to stress localization at the discontinuity and severe cracking might occur there under intensive earthquakes. Hence abrupt change in dam face slope should be avoided.

Based on the above consideration, we can adjust the dam profile to reduce tensile stress in the dam body. For the dam section shown in Figure 1, a gentler upstream slope could reduce the tensile stress at the heel of dam body. At the same time, the slope should transit smoothly to the vertical part of upstream face to avoid stress localization at discontinuity. From this point of view, a suitable upstream slope is shown in Figure 5. The fillet slope near the heel is gentler than that of original dam but it becomes steeper gradually and transits smoothly to the vertical part of upstream face.

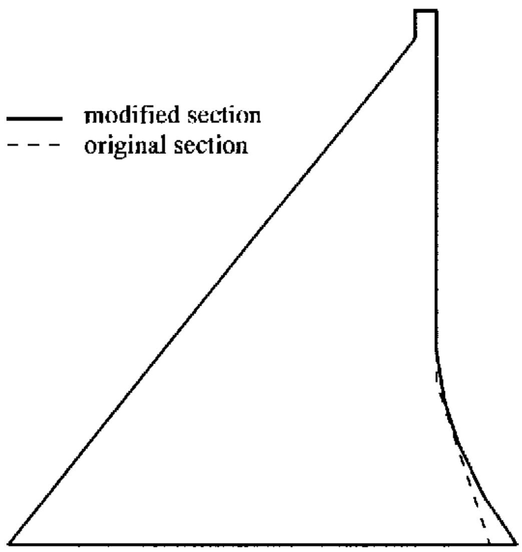


Figure 5. Modified profile of dam section

With the modified profile shown in Figure 5, seismic response of the dam is calculated similarly. There is no cracking occurred in the dam body during the earthquake. To investigate the effect of section modification, linear earthquake response of dam body with the original and modified section is compared. The maximum tensile stresses at the heel and upstream discontinuity for the two sections are compared in Table 2. It can be seen that the improvement of the fillet slope evidently reduces tensile stress at the heel as well as at the upstream discontinuity.

Table 2. Comparison of maximum tensile stress (MPa)

	original shape	modified shape
heel	3.43	2.08
upstream discontinuity	2.49	2.02

The above example demonstrates that tensile stress in the dam body is dependent on the dam profile, and that a suitable shape of upstream slope can help us to keep tensile stress at lower level even under large earthquakes.

Thus, the option of dam profile is a very important factor in the design of concrete gravity dams in order to increase the earthquake-resistant capacity of dam body.

LOCAL REINFORCEMENT

Reinforcing steel is widely used in the modern construction of concrete structures, including concrete gravity dams to improve the cracking-resistant behavior of dam body. Effects of reinforcing steel on preventing cracks in concrete gravity dams are discussed here.

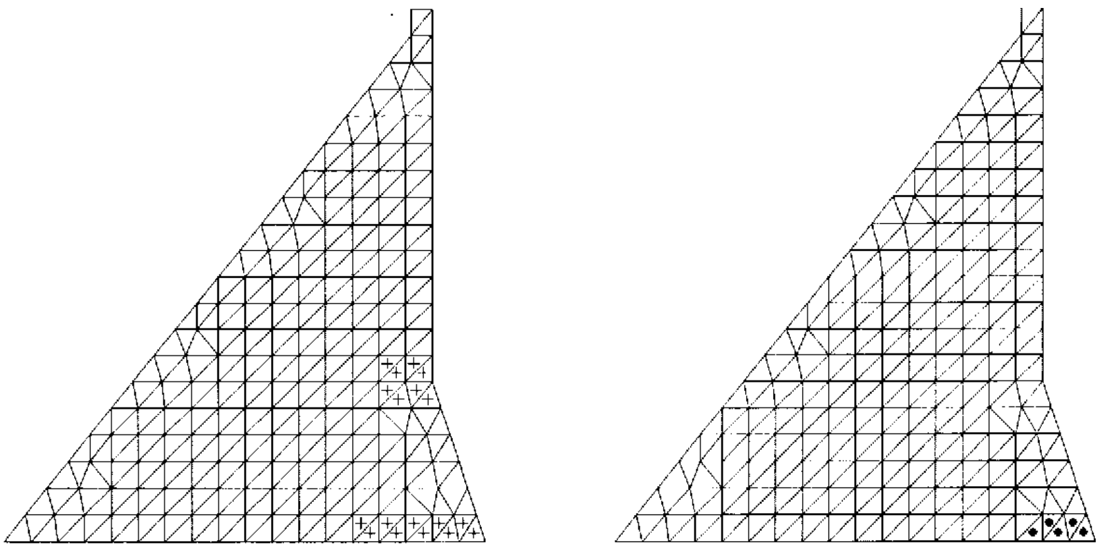
In the analysis of reinforced concrete, bond slip between concrete and steel is disregarded, and the reinforcement bars are smeared throughout the concrete element [Suidan and Schnobrich, 1973]. The property of steel can be expressed as

$$D_s = E_s \begin{bmatrix} p_x & 0 & 0 \\ 0 & p_y & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{10}$$

in which E_s is the elasticity modulus of steel, and p_x and p_y are the median ratios of steel bars in the x and y directions. This property will be added to that of concrete to represent the mixed property of reinforced concrete.

The elasticity modulus of steel is generally 200000MPa. In this example, the diameter of steel bars is taken as 50mm and the maximum aggregate size of concrete is assumed to be 120mm. The pure interval between steel bars, which should be larger than 1.5 times of the maximum aggregate size of concrete, is set to 200mm here. Then the median ratios of steel are 0.0314 in the x and y directions.

Based on the above assumption, seismic response of the reinforced dam is calculated. From economical point of view, steel bars are usually allocated at possible cracking region only, as shown in Figure 6(a). With the local reinforcement, cracking does not occur at the upstream discontinuity, but occurs along the dam base during the earthquake, as shown in Figure 6(b). According to Table 2 showing linear calculation results for the plain concrete dam, the maximum tensile stress at the upstream discontinuity is a little higher than the strength of concrete, but the maximum tensile stress at the heel is much higher than the strength. Consequently, adding the steel bars cannot prevent the occurrence of cracking due to the tensile stress. On the other hand, the cracking region along the dam base in the case with steel bars is smaller than that in the case without steel bars, showing that adding the steel bars is effective to prevent propagation of cracks.



(a) local reinforcement (b) cracking of dam body

Figure 6. Local reinforcement and cracking

According to the linear calculation result, tensile stress exceeding the strength of concrete in the dam body just develops in a small region. But because of the brittle feature of plain concrete, the occurrence of cracking causes stress redistribution in the structure. The stress redistribution leads to the propagation of crack, and the highly tensile stress in a small region might cause large cracking region in the plain concrete dam. Reinforcing the possible cracking region by steel bars could resist the stress redistribution and reduces crack propagation. As a result, the cracking region can be limited by reinforcing with steel bars.

Although earthquake-induced cracking should be prevented, if possible, to ensure linear response of dam body under maximum credible earthquakes is sometimes too expensive or impossible. In such a case, localized cracking of concrete may be accepted under maximum credible earthquakes if the cracking is far from endangering the integrity and safety of dam body [USBOR, 1977]. From this viewpoint, local reinforcement is an effective method for the seismic strengthening of concrete gravity dams.

POST-TENSION TECHNIQUE

Post-tension technique is an effective method to improve the load carrying capability of concrete structures and it is already applied to concrete gravity dams to rehabilitate earthquake-induced cracking. For the seismic strengthening of concrete gravity dams, the reasonable arrangement of cables and the adequate post-tension forces must be carefully determined by numerical simulation, to ensure the dam safety against cracking.

Generally, post-tension cables should be arranged in the direction perpendicular to the possible cracking. For the concrete gravity dam shown in Figure 1, horizontal cracking will occur at the heel and/or upstream discontinuity during the near-field earthquake, as predicted in nonlinear analysis. Thus cables to prevent the upstream cracking are arranged in the vertical direction.

The requirement of post-tension force must be evaluated carefully because over-strengthening might cause cracking of the dam body. To check the effect of strengthening, seismic response of the post-tensioned dam is simulated numerically. Initial tension force in cables is simulated as concentrated load at the anchorage. Cables are modeled as truss elements which have axial stiffness only [Leger and Mahyari, 1994]. The amount of cables, their location and post-tension force are adjusted until the scheme satisfies the objective of allowing no cracks in the dam body during the earthquake.

A post-tension configuration to prevent cracking of dam body under the earthquake is shown in Figure 7. The diameter of the cables is 63mm. Four cables are densely arranged near the heel of dam body because highly tensile stress will occur there during the earthquake. The post-tension forces in the cables are listed in Table 3. From P3 to P6, the post-tension force increases gradually to avoid over-strengthening.

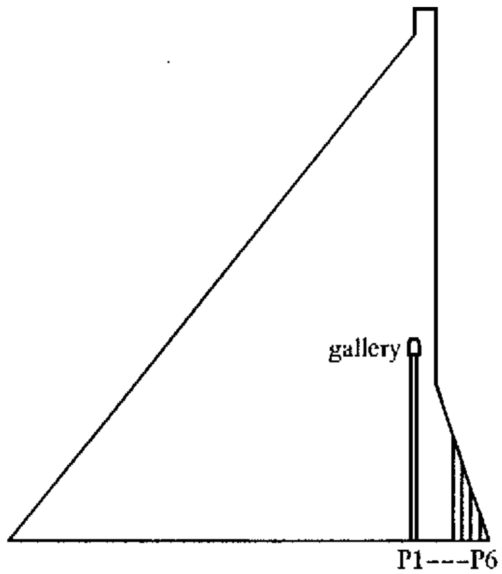


Figure 7. Post-tension configuration

Table 3. Post-tension forces in the cables (kN)

P1	P2	P3	P4	P5	P6
2000	2000	1000	1500	2000	2500

The difference between the post-tension technique and other strengthening method is that the post-tension force is applied to the dam body as external force. Because of this, the post-tension scheme needs to take into consideration of the structural resistance, in order not to endanger the safety of dam body.

CONCLUSIONS

To improve the dam safety under very strong earthquakes, seismic cracking and strengthening of concrete gravity dams is discussed in this paper. Numerical simulation shows that concrete gravity dams are possible to experience cracking during large earthquakes and the suggested measures are effective to prevent the occurrence and propagation of cracking in concrete gravity dams. Conclusions can be listed as follows.

(1) Concrete gravity dams are likely to experience cracking under intensive excitations, especially at the heel of dam body and upstream discontinuity.

(2) A gentle and smooth upstream face could reduce the tensile stress in the dam body and avoid the occurrence of cracking.

(3) Reinforcing bars cannot prevent the occurrence of cracking under highly tensile stress, but it can resist the propagation of cracks and reduce the damage of dam body.

(4) Post-tension cables can strengthen the dam body effectively, if it is adequately designed.

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