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SEISMIC FRACTURE ANALYSIS AND POST-TENSION REHABILITATION OF CONCRETE GRAVITY DAMS

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ABSTRACT

If the seismic stability of concrete gravity dam is threaten, post-tension anchors must often be designed to increase the safety against cracking. Dynamic nonlinear analyses are then useful to determine the potential paths for crack extension and failure mechanisms allowing the optimization of the post-tensioning system. Spectrum-compatible ground motion acceleration time histories, that might be defined from historical records, Fourier modified records, or synthetic records, must be specified as input to perform transient crack propagation analysis. However, the cracking response is sensitive to the details of the time variations of the input motions. To identify the type of input motion that is critical for earthquake resistant design of gravity dams, this paper first present a study of the sensitivity of the cracking response of a typical 90m gravity dam to the method selected to define the spectrum-compatible accelerograms. The efficiency of various post-tension strengthening schemes for seismic rehabilitation are then investigated from transient seismic fracture analyses.

KEYWORDS

Concrete cracking, gravity dams, spectrum-compatible accelerograms, post-tensioned anchors.

INTRODUCTION

The accepted design philosophy, as stated in several dam seismic safety guidelines (BRE 1991, CEA 1990, NRC 1990), is to expect a generally linear elastic response under moderate intensity earthquake, and controlled damage under the maximum credible earthquake without endangering the ability of the dam to retain the reservoir. Accordingly, all guidelines recommend a progressive approach starting with simple linear elastic models of the dam-foundation-reservoir systems, followed by nonlinear models to consider concrete cracking, if the design earthquakes induce inertia forces exceeding the elastic strength capacity of the structure. Nonlinear crack propagation analysis allows to identify cracking patterns, associated failure mechanisms and related safety margins on a rational basis. When a concrete dam is believed to be seismically unsafe or has been damaged by an earthquake (ie. Sefi Rud, Iran 106m with 24 buttresses) post-tension anchors are often used to increase the safety against cracking and restore the monolithism of the structure. The number of cables, their location, their length, and the magnitude of the required tension forces must be carefully determined to ensure the seismic safety of post-tensioned dams.

Although transient fracture analysis is the most appropriate approach for a comprehensive safety evaluation of concrete dams, several reservations are generally expressed concerning the present state-of-the-art of nonlinear seismic analysis as currently available for industrial applications: (i) the results are sensitive to the selected concrete constitutive model, (ii) the results are sensitive to the time variation and frequency content of input motion, and (iii) the predicted response is strongly influenced by the initial conditions (including the presence of post-tensioned anchors) and past loading history of the dam-foundation-reservoir system analyzed. Research needs have thus been identified to (i) develop improved dynamic fracture concrete constitutive models, (ii) assess the sensitivity of the predicted cracking response to the details of input ground motions, and (iii) investigate the influence of post-tension anchors on the predicted safety margins. To this end, this paper presents the nonlinear seismic responses of a typical plain and post-tensioned 90m concrete gravity dams to historical records that are characteristics of Eastern North American conditions and smooth spectrum-compatible records obtained from Fourier modified and synthetic accelerograms. A constitutive model based on a smeared implementation of nonlinear fracture mechanics principles is used to simulate concrete cracking of the dams under seismic loads. Several indicators such as the critical peak ground acceleration, CPGA, that corresponds to the acceleration level required to induce dynamic instability in the system, the seismic energy response, and the cracking profiles have been investigated to (i) characterize the structural response, (ii) identify the type of input motion that is critical for the earthquake resistant design of gravity dams, and (iii) evaluate the efficiency of various post-tension strengthening schemes for seismic rehabilitation.

GENERATION OF SPECTRUM COMPATIBLE ACCELEROGRAMS

To perform seismic safety evaluation of concrete dams, the expected seismic excitations at the site are generally first defined in terms of smooth design spectra. However, ground motion acceleration time histories are required for a comprehensive study of the linear time variation of the stress response, as well as the cracking response when performing nonlinear analyses. The frequency content and the presence of harmonic and/or long acceleration pulses are likely to be very detrimental to the dynamic stability of a cracked dam. It is uncertain to which extent the detailed time variation of ground accelerations, obtained either from historical records, Fourier modified records, or synthetic records, all scaled or adjusted to provide compatibility with the selected smooth design spectra, might influence the selected damage indices and cracking response of the system. Once a smooth design spectrum has been defined using suitable criteria, the following procedures can be used to generate spectrum-compatible accelerograms:

(i) Scaling of historical records to specified ground motion or spectral intensity parameters. The advantage of this approach is to preserve the characteristics of real earthquakes such as the time evolution of the frequency content. Severe drawbacks include the large number of records required to cover the target spectrum, and the lack of such suitable strong motion records to represent the seismic motion of many regions of the world.

(ii) Modification of the magnitude of the Fourier spectrum coefficients of suitable historical records while preserving the original phase angles. The resulting time history maintains some of the characteristics of the original time history but demonstrates a better spectrum-compatibility than that of the original accelerograms.

(iii) Generation of a filtered white noise signal having a spectrum that closely matches the target spectrum (SIMQKE 1976). The main advantage of this approach is the excellent spectrum-compatibility that might be achieved, but this is often at the cost of exhibiting excessive numbers of acceleration pulses and unrealistic phase relationship (ICOLD 1989). This approach is recommended by BRE (1991). It has been widely used for linear analysis of concrete dams. However, ICOLD (1989) states that the use of synthetic accelerograms is not recommended for nonlinear analysis of dams, specially if such aspects of real records such as the change of frequency content over time is important. Nevertheless, several authors have used synthetic records to study the cracking response and dynamic stability of concrete dams.

CONCRETE MODEL TO PREDICT SEISMIC CRACKING

A smeared implementation of a concrete model based on nonlinear fracture mechanics principles is used to represent crack formation and propagation in the dams. A tensile strain softening law is adopted to describe the fracturing process when the tensile stresses exceed the tensile strength. The basic parameters of this model are the fracture energy, G_f, the tensile strength, σ_t, and the softening law. The problem of mesh objectivity is tackled by adjusting the area under the average stress-strain curve for a finite element undergoing fracture such that the dissipated fracture energy, G_f, for unit area of crack extension remains independent of the element characteristic dimension, h_c, defined as the square root of the element area. The key features of the constitutive model developed for seismic fracture analysis of gravity dams are presented in Fig.1. For a more detailed review of the concrete constitutive model used in this study and its finite element implementation for nonlinear seismic analysis of gravity dams, the reader is referred to Bhattacharjee and Léger (1993).

Energy balance computations are performed at each time step to monitor the numerical stability of the model, and to assess the relative importance of energy components due to kinetic (E^K), damping (E^D), nonlinear restoring forces (E^R), seismic input (E^Q), and pre-seismic loads (E^P). The error in energy balance is used as an index to assess the degree with which the global equilibrium is maintained in the solution process:

$$EBE = \frac{(E^Q+E^P)-(E^K+E^D+E^R)}{E^Q} x100\% \qquad (1)$$

A significant error in the energy balance indicates the presence of severe damage, but does not necessarily mean a dynamic instability of the actual structure. However, it certainly indicates that the basic assumptions of the constitutive model (i.e. small displacement continuum theory) are no longer valid.

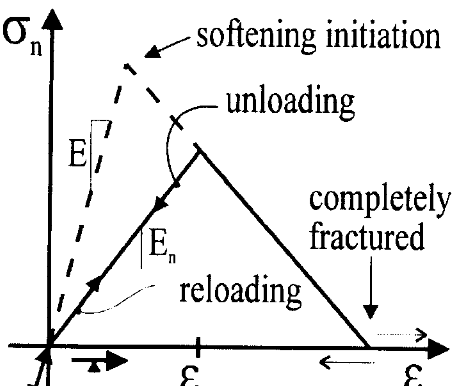


Fig.1 Tensile stress-strain response of concrete.

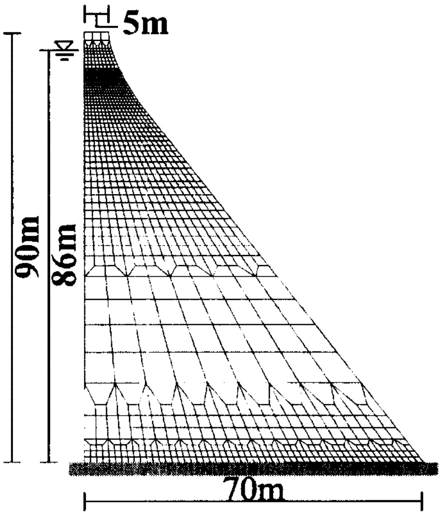


Fig.2 90m dam model.

SYSTEM ANALYZED

A typical 90 m high concrete gravity dam, that approximately corresponds to the taller gravity dams in Quebec (Canada), is selected as the basic structure for this study. A two-dimensional plane-stress idealization, assuming a rigid foundation condition, is considered to compute the seismic response of the finite element model shown in Fig.2. In addition to the self-weight and hydrostatic pressure, Westergaard added masses are used to represent the hydrodynamic interaction forces. The following concrete properties are assumed in smeared fracture analyses: elastic modulus $E=27960$ MPa, Poisson's ratio $\nu=0.2$, mass density$=2400$ kg/m^3, tensile strength $\sigma_t=2$ MPa, fracture energy $G_f=200$ N/m, with dynamic magnification factors for σ_t and G_f equals to 1.2. The dynamic equilibrium equations are integrated with a time step of 0.0025 sec, using the Alpha method with an algorithmic damping parameter $\alpha = -0.2$. The natural period of vibration of the finite element model is $T_1=0.26$ sec. An elasto-brittle damping model with 5% damping in the fundamental mode of the dam alone has been considered to define the structural damping matrix.

RECORDED AND SIMULATED EARTHQUAKE GROUND MOTIONS

To study the cracking response of dams, a smooth design spectrum has been defined for a strong event of moment magnitude M7, occurring in Eastern North America with an epicentral distance of 20km and a focal depth of 15km. The Atkinson and Boore (1990) attenuation functions have been used to compute directly the spectral ordinates and the peak ground motion parameters (PGA=0.5g). If historical records are used as input motion, they should therefore be ideally representative of an M7 Eastern earthquake recorded on rock at 20 km from the source. However, the worldwide database is deficient in large magnitude near source records compatible with the Eastern North-American (ENA) condition which is very rich in high frequency motion as compared to typical Western records. Typical ENA historical accelerograms from the 1989 Nahanni (M6.9) and the 1988 (M5.9) Saguenay earthquakes were considered. Due to the lack of other suitable large magnitude near source ENA record, a US West coast earthquake (Loma Prieta 1989 (M6.9)) has also been considered for comparison purposes (Léger and Leclerc 1995). Figure 3. shows the elastic spectra for the historical and Fourier modified input accelerograms using 5% damping. It shown (Fig.3b) that excellent spectrum compatibility is obtained from all records over the short period range (0.04-0.5s) except for the Loma Prieta Fourier modified record for period smaller than 0.1s. This is because the deficiency in high frequency motion of Western North America records is inherent and cannot be compensated by the modification of the Fourier spectrum. However, good spectrum compatibility to Eastern North America spectra may be achieved for periods longer than 0.1s. The spectra of the synthetic records (not shown) exhibited excellent spectrum compatibility over the complete period range.

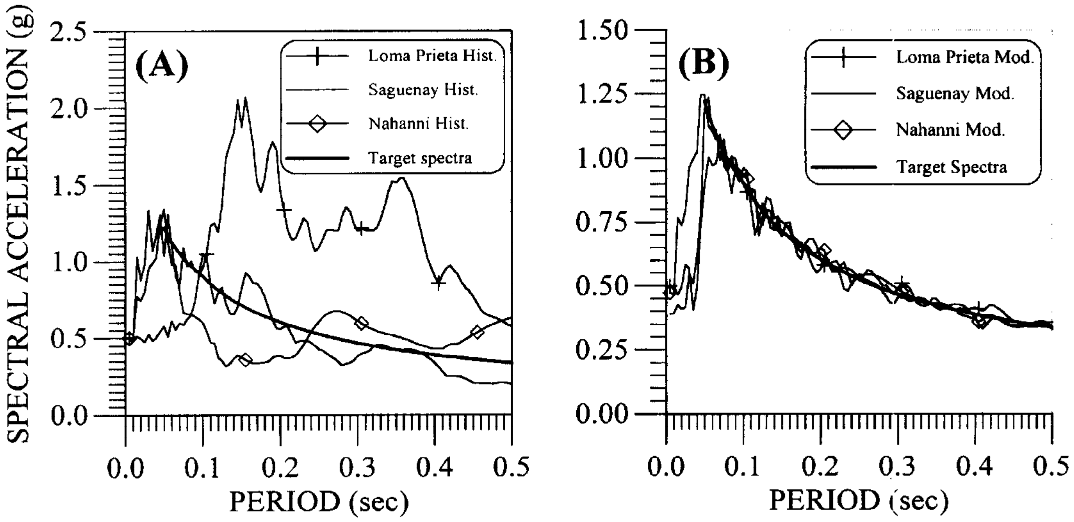
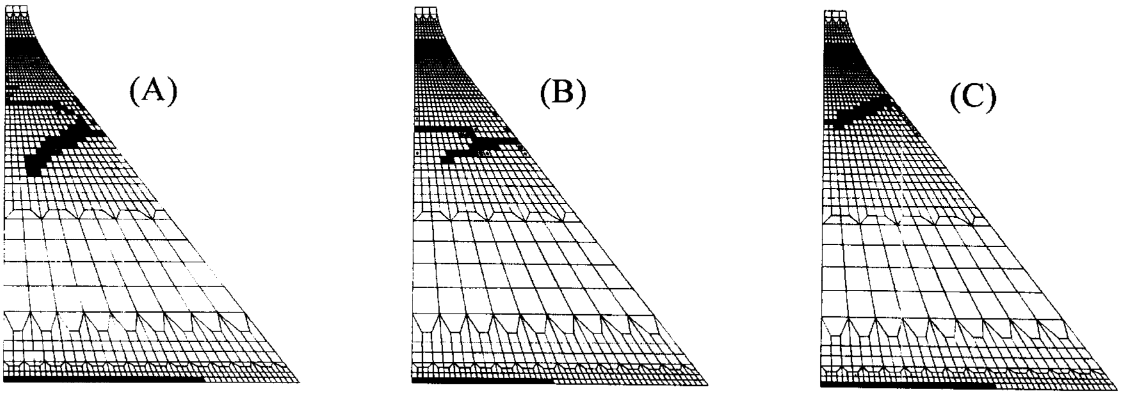


Fig.3 Elastic response spectra of input accelerograms (damping=5%).

SEISMIC RESPONSE ANALYSIS OF PLAIN DAMS

The seismic response analysis has been carried out by scaling each input record, to progressively increase the intensity of ground shaking by increment of about 0.05g and induce cracking in the dams but with an EBE (Eq.(1)) not exceeding 3%. This criteria indicates that severe cracking occurred but that dynamic stability of the cracked components is maintained within the limits of the constitutive concrete models that is based on a small displacement continuum mechanics theory. The time histories of crest displacements and energy response components, as well as the cracking profiles, were examined for each analysis. The results are summarized in Table 1 which report the maximum input energy E^Q and other ratios of maximum values. The critical PGA (CPGA) and the energy response corresponds to the last run that provided convergence of the solution, while a further application of a small PGA increment typically caused EBE far in excess of 10%. Figure 4 shows some of the crack profiles that were obtained.



Saguenay Hist.
CPGA=0.65g

Saguenay Mod.
CPGA=0.45g

Synthetic
CPGA=0.55g

Fig.4 Cracking profiles.

Table 1. Seismic response.

Earthquake	Dam	CPGA (g)	Crest disp. (mm)	EBE (%)	E^Q (kN·m)	E^D/E^Q (%)	E^K/E^Q (%)	E^F/E^Q (%)
(A) Historical Records (horizontal components)								
Loma Prieta	90m-s	0.20	31	1.10	1160	82.8	18.5	2.76
Saguenay	90m-s	0.65	34	0.60	1200	93.3	27.5	4.33
Nahanni	90m-s	0.57	44	0.80	1080	70.4	90.7	4.72
(B) Historical records with modified Fourier amplitude spectra (horizontal components)								
Loma Prieta	90m-s	0.45	28	0.60	1050	94.3	11.0	3.62
Saguenay	90m-s	0.45	30	1.10	1240	93.6	19.4	4.11
Nahanni	90m-s	0.65	37	0.90	1660	95.8	25.0	3.31
(C) Synthetic time histories (filtered white noise) (horizontal components)								
Synthetic 1 (S1)	90m-s	0.45	25	0.10	800	95.0	25.6	2.00
Synthetic 2 (S2)	90m-s	0.55	47	2.00	1620	91.4	25.9	3.40
Synthetic 3 (S3)	90m-s	0.50	34	1.70	1140	89.9	24.1	5.18
(H) Saguenay historical with modified Fourier amplitude spectra (hor. + vert. components)								
Saguenay (H + V)	90m-a	0.33	25	0.80	775	93.5	23.9	2.39
Saguenay (H + V)	90m-s	0.55	55	1.85	2200	90.9	14.3	4.59

Response to Historical Records

The CPGA is dependent upon the predominant period of strong shaking of the earthquake versus the natural period of the system. The Loma Prieta record containing a significant amount of energy near the fundamental period of the system ($T_1=0.26$ sec), as shown by its elastic spectra in Fig. 3a, has the lowest CPGA (0.2g). The Eastern records, with higher frequency content, have much less energy near the fundamental period and thus require larger intensity levels (average CPGA=0.61g) to induce a dynamic instability in the system. The cracking profiles shown in Figs.4a to 4c indicate that the failure mechanism is formed of two main cracks, one at the base and one in the upper zone of the dam. In each case, the base crack extended approximately 66% of the base. The maximum input energy, E^Q, remained within a relatively narrow band ($1080 \leq E^Q \leq 1200$ kN-m) for all analyses. The average amount of energy dissipated by cracking, E^F, represents 3.9% of the input energy, while the ratios of the energy dissipated by viscous damping to the maximum input energy varied from 70.4% to 93.3%. It was observed that significant cracking initiation and propagation are associated with sharp pulses in kinetic energy. The Nahanni (historical) record contains a sharp acceleration pulse early in its time history that imparts a high value of input energy, E^Q, to the system. Table 1 shows that 90.7% of this E^Q energy impulse is transformed in kinetic energy.

Response to Fourier Modified and Synthetic Records

The Fourier modified records initiated crack propagation at approximately the same level on the downstream face as that obtained from the parent historical records (Fig.4b). The average CPGA is now 0.51g for the three records, a value slightly below the 0.61g obtained from the parent Eastern records. The modified Loma Prieta record, with a CPGA=0.45g, now provides results comparable to the Eastern records. The input energy, E_Q, now varies in a wider range but there is much less variations in the relative energetic responses (E_D/E_Q, E_K/E_Q, E_F/E_Q) of the system.

The synthetic records produced similar cracking profiles among themselves (Figs.4c), but were slightly different from those obtained from the historical or the modified records, inducing crack propagation at an upper level on the downstream face. The average CPGA is 0.50g with a variation of ± 0.05g from each record. However, there was a significant variation in maximum crest displacement while using record S1 (25mm) as compared to the value obtained from record S2 (47mm). Considering the variations observed in CPGA, cracking profiles and energy responses, it appears that at least three synthetic spectrum-compatible accelerograms should be used to bound the cracking response and earthquake resistance of concrete gravity dams.

Influence of Geometry on Cracking Response

These analyses were performed using the Saguenay Modified record but a vertical (V) component of input motion was added to the horizontal one. The addition of a V component slightly reduced the CPGA (from 0.65g to 0.55g). For this dam when a sharp angle that favours crack initiation is used on the downstream face (model 90m-a), the CPGA was reduced to 0.33g as compared to 0.55g for the model with a smooth downstream face (90m-s). The cracking profile of the 90m-a model involves a straight crack initiated at the change of slope that separates the crest mass from the rest of the dam (not shown). Sharp angles that favours stress concentrations might thus significantly influence the seismic cracking of gravity dams.

SEISMIC RESPONSE ANALYSIS OF POST-TENSIONED DAMS

To illustrate the seismic response of post-tensioned dams, parametric analyses were performed on the 90m dam considering a uniform concrete dynamic tensile strength of 2.4 MPa. The dam models were analyzed for the horizontal and vertical accelerograms of the Fourier modified Saguenay (1988) earthquake with HPGA and vertical peak ground accelerations (VPGA) initially set at 0.5g and 0.33g, respectively. The intensity of earthquake ground motion was subsequently increased progressively to induce dynamic instability in the dam models as indicated by the cracking profile, related crest displacements and excessive error in energy balance computations (above 3%). The post-tension cables were modelled as initially stressed truss elements with axial stiffness only. The dowel action was ignored and unbounded conditions were enforced in the tangential cable direction by defining separate degrees-of-freedom for the cable and the dam. Different amount and distribution of post-tensioning forces were determined to satisfy the objectives of (i) allowing no crack penetration in the upper part of the dam most vulnerable to seismic damage, (ii) improving the global stability by an increase in dam-foundation normal contact stress, and (iii) allowing controlled damaged during the MCE (Léger and Mahyari 1994). Some results are presented below.

Figure 5a shows the cracking response in the plain structure for HPGA=0.5g. There is almost an all-through crack in the upper third region of the dam. At the dam-foundation interface, the crack extends over 60% of the base. The HPGA to obtain an excessive EBE is 0.58g. Although extensive cracking took place at a HPGA=0.5g, no dynamic instability is expected. It might however be desirable to design post-tensioning systems to prevent seismic crack propagation in the upper part, and produce a global failure mechanisms at the dam-foundation interface.

A post-tension configuration to avoid crack propagation in the upper part of the dam when subjected to a HPGA=0.5g is shown in Fig.5b. The nonlinear analysis prediction of the required amount of post-tension force to avoid crack propagation in the upper part of the structure is approximately 50% smaller than the amount predicted from preliminary linear finite element analysis to maintain tensile stresses below 2.4 MPa. The main reason is that the base crack provides a seismic isolation of the dam reducing the inertia forces in the structure. The crack length at the base of the post-tensioned dam is similar to that of the plain concrete dam. Thus, the partial post-tensioning of the upper part has no significant effect on the global stability of the dam. The HPGA at failure is 0.82g and results in an all through cracking in the upper part and at the base of the structure (Fig.5c). Post-tensioned cables increased the ultimate HPGA from 0.58g to 0.82g. The post-tension forces were reduced by 20% in subsequent analyses to allow crack propagation in the upper part of the structure with a HPGA=0.5g (Fig.5d). Post-tension now prevents crack penetration at the upstream face, and controls the crack propagation at the downstream face.

In all analyses, the maximum fluctuation of stresses in upstream and downstream cables was about 2% of the initial static values. The relative sliding displacements remained small along the upstream crack profiles. This suggests that rupture of a post-tension cable by local shearing is an unlikely event.

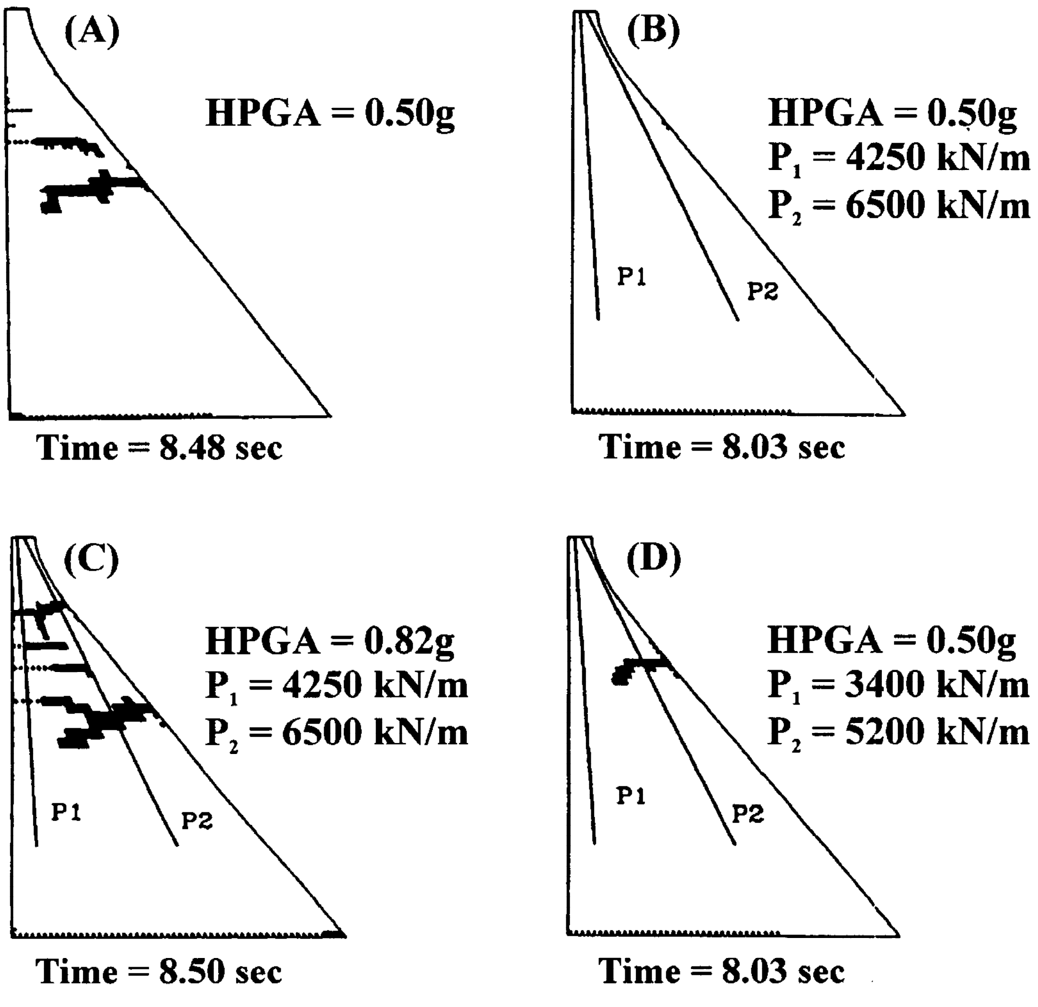


Fig.5 Seismic response of plain and post-tensioned 90m dam.

CONCLUSIONS

In this study, the cracking response of gravity dams three basic types of input accelerograms have been examined. The efficiency of different post-tension strengthening schemes has also been examined. The following conclusions can be made:

Spectrum-compatible accelerograms should reproduce, as far as possible, the essential ground motion characteristics inherent in historical records. The Fourier modified records tend to give a closer response to that obtained from the scaled historical records than that obtained from the synthetic accelerograms. In the absence of historical records to be modified, synthetic records can be used. Considering the variability in the seismic response of gravity dams when cracking is considered, at least three records should be used in a seismic safety evaluation.

The presence of sharp angles or other sources of stress concentration on the downstream face of gravity dams generally favours crack initiation and propagation at lower PGA values than when a smooth downstream face is used.

In seismic analysis of post-tensioned gravity dams, a single cable layout near the upstream face may not be sufficient to control cracking from the downstream face. Downstream partial post-tensioning is an essential element if cracking initiated from the downstream face is to be prevented or minimized. It maintains the local stability of the upper part of the dam by preventing the crack penetration through the dam width. For the system analyzed, no significant stress fluctuations occurred in post-tension cables and the shear displacements at the crack plane crossing the cables are small such that the structural integrity of the cables should be maintain during the design seismic event.

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