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EARTHQUAKE RESPONSE OF CONCRETE GRAVITY DAM-RESERVOIR SYSTEM - NONLINEAR ANALYSIS

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ABSTRACT

Finite element procedure was used to model the nonlinear dynamic response of gravity concrete dam-reservoir system. Nonlinear behaviour of the system was achieved by nonlinear stress-strain model of concrete which was proposed by Mander ,1984 , the nonlinearities due to tension cracking in dam which modelled by Smearing techniques with subsequent opening closing and sliding , and the nonlinearity in compressible water in reservoir due to cavitation and further more the foundation of the dam was modelled as a rigid rectangular massless plate attached to three dimensional viscoelastic half-space. The sedimentary material at the bottom of the reservoir were modelled as absorption which partially absorb the incident hydrodynamic pressure waves . Also, the analysis includes the effects of dam-reservoir interaction and the radiated hydrodynamic pressure waves in the far field of the reservoir at truncated boundary . A computer program was developed and coded as (NLDRS-C) . The program was justified with results published by El Aidi and Hall , 1989 . Numerical solutios were obtained to investigate the effect of nonlinearity on response of the dam-reservoir system. It was found that including of nonlinearity of concrete into the behaviour of the system increases the horizontal displacement of the dam crest by about 18 % .

KYWORDS

Seismic analysis, two dimension model, soil structure interaction, concrete dams, nonlinear response, concrete crack, hydrodynamic response, overtopping .

INTRODUCTION

Linear dynamic analyses of gravity dams show that earthquake motions may produce tensile stresses in concrete dams that exceed the permissible tensile strength of concrete . Also, observations of Koyna and Hsinfengkiage dams (Hall, 1988) indicated that induced cracking due to earthquake excitation are inevitably. Thus non-linear analyses are required to understand cracking phenomenon and its effect on the stability of the dams . In such cases linear analysis nolonger valid because tensile cracks formed in concrete affecting the dynamic response of the dam.

Tsai and Lee ,1991 have developed a nonlinear formulation, based on the velocity potential for fluid . The nonlinear surface waves and exact transmitting boundary conditions were introduced . They concluded that the nonlinear response of a rigid dam-reservoir systems is very much dependent on the loading type. Although these analyses identified the regions of the dam where large tensile stresses would occur, their formulations could not predict the extent of subsequent cracking which the dam may suffer during a particular ground motion expect (El-Aidi and Hall, 1989) . Prediction of the extent of a crack and its significance for the future safety of a dam possesses formidable analytical difficulties . Nevertheless , the practical importance of obtaining such data to prevent catastrophic failure is becoming increasingly evident for most of the existing dams .

El-Aidi and Hall, 1989 have studied the nonlinearity response of the dam due to cracking of concrete only using smeared crack model employing equivalent tensile strength based on fracture mechanics criteria . Several cases of cracking are considered to obtain insight into the nonlinear dynamic behavior of the system. Rocking and sliding of fully cracked sections are investigated, and possible modes of failure are identified . Also, cavitation in water are considered . Nevertheless (El-Aidi and Hall, 1989), reported that improvements in nonlinear mathematical models of concrete dams are still needed .

The very few experimental data on cracking in concrete gravity dams , appear in literature, have a shortcoming due to the lack of details in the description of cracking and in the structure drawings provided in cited references which prevent a complete interpretation of what actually happend . (Hall , 1988) has reported that there were a few experimental work on a small models of dams without water in reservoir, and on a small models of dam-reservoir systems . Hall, 1988 also, quoted that numerical analysis including nonlinearity due to cracks has been used by many researchers as an attempt to illustrate the affect of cracking on dynamic response of concrete gravity- dam-reservoir system .

Mlakar, 1987 modeled the nonlinearity response of dams due to , only , cracking, using an equivalent tensile strength based on fracture mechanics criteria, and employing smeard cracking incorporated special discontinues shape functions, to overcome some of the extraneous stiffness of a finite elements containing cracks. The results on Pine Flat Dam are not intuitive because the stress release which accompanies cracking relieves the surrounding tensile stresses except those ahead of the crack, nevertheless the crack propagate in narrow zone . The author also, indicated that it is difficult to model accurately the reservoir cavitation because of the lack of knowledge and experimental data required to understand the actual physical mechanism involved .

Theoretical studies by (Clough and Chang, 1984) assumed that cavities are containing only water vapour and air and confined to the dam face . The hydrodynamic pressure formulation as an independent variable was based on the assumption of water incompressibility and all degrees of freedom away from the dam were condensed out , where is possible . They pointed out that since water compressibility can significantly affect the water pressure response , it should be included in cavitation studies .

Nonlinear finite element analysis of Norris dam including compressive stress-strain nonlinearity, hysteresis and smeared cracking , was reported by, (Agbabian, 1975) . A moderate horizontal excitation with 0.2 g peak acceleration was considered . Dynamic water pressures were computed from linear analysis and input as external forces on the dam. This is an approximate procedure involving unknown error .

So, the required analytical procedure should therefore not only be accurate in its numerical representation of the crack problem but should also, be efficient in studying dynamic crack propagation . Thus the work presented in this paper are devoted for the earthquake response of a concrete gravity dam-water-foundation system with nonlinear properties of concrete and water cavitation . The influence of nonlinear behaviour of concrete associated with cracking with subsequence opening closing and sliding , on dam-water- interaction with the possible modes of failure are also , studied. The developed computer program, is subsequently verified by comparison of a well documented case history .

MATHEMATICAL MODELS:

The idealization of the geometry of the dam-reservoir system under consideration is depicted in Fig. 1 . The dam and the water are idealized as planar , two dimensional finite element discretization , a standard displacement and a mixed displacement-pressure formulations are used to represent dam and water element respectively in which the pressure in fluid element is approximately as an independent variable .

Water Cavitation Model

The stat of water in reservoir affects the dynamic response of the dam, where absolute water pressure in fluid adjacent of the dam face can not develop below the vapour pressure of the fluid , (-2.3 KN/ m^2) thus some amount of cavitation can be expected in the reservoir. The importantace of cavitation in dam-reservoir systems is the possible effects on the hydrodynamic forces acting on the dam which play an important role in the dam response .

The mathematically bilinear model is used to model the cavitation (Malkar, 1987 , Clough and Chang, 1984) , and the governing equation for an inviscid fluid undergoing small amplitude and irrotational motion can be satisfied to momentum balance equation. However the finite element discretization of the fluid can be obtained from the weak form of the governing equation , and specifying the boundary conditions as shown in Fig. 1. (Abdrabbo and Ali , 1995) . So one can expresses the general governing equation assembly of element equations as ,

$$M_f \ddot{U}_f + C_f \dot{U}_f + K_f U_f + F_f = - (M_f I \ddot{u}_g + P_f) \qquad (1)$$

where, M_f , C_f , and K_f are assembled from mass, damping and stiffness element matrices , U_f the fluid relative displacement, F_f the vector of nonlinear restoring forces, and P_f hydrodynamic pressure normal to the dam interface .

It is worthnote that the equation of motion of water, (1) is time and boundary conditions dependent . Thus the boundary conditions of water in reservoir should be defined . Linear surface wave is considered on free water surface S_4, where the initial pressures normal to the surface are vanished . While the infinite water domain is truncated some distance upstream of the dam at a transmitting boundary which accounts for the effect of the far field of the fluid domain at boundary S_3 . Using time-domain semianalytical method (Tsai and Lee, 1991) . The reservoir is provided with some absorption at the bottom, Fig. 1. through which a damping boundary condition is introduced to consider the effect of sedimentary material on the bottom of the reservoir . Finally, the interaction forces and the coupling terms on dam- water interface S_1 is considered .

Nonlinearity Concrete Model

In this study the nonlinear four-parameter model of uniaxial stress-strain of plain confined concrete which reported by (Mander, 1984), Fig. 2 is used . The model expressed as ,

$$f_c = \frac{\bar{f}_{cc} \times r}{r - 1 + x^r} , \qquad (2)$$

for Monotonic loading, associated with strain ε less than zero where , $x = \varepsilon / \varepsilon_{cc}$, $r = E_c / (E_c - E_{sec})$, $E_{sec} = f_{cc} / \varepsilon_{cc}$ in which , $\bar{f}_{cc}$ peak confined concrete strength ($\bar{f}_{cc} = \bar{f}_{co}$, the uniaxial unconfined concrete strength) , ε_{cc} strain at the confined strength ($\varepsilon_{cc} = \varepsilon_{co}$, strain corresponding to uniaxial unconfined concrete strength) , E_c initial tangent modulus of elasticity , f_c the concrete stress and ε the uniaxial strain . But for tension loading Fig. 2 , where the strain is greater than zero ($\varepsilon > o$) a linear stress- strain relation is assumed provided that the tensile strength f_t has not been exceeded ,

$$f_c = E_c \varepsilon \quad ; \quad f_c < \bar{f}_t \quad , \text{otherwise} \quad f_c = 0 \qquad (3)$$

If the reversal of loading is from the compression loading curve which follow (2) , with a plastic strain ε_{pl} based on the reversal coordinate (ε_{un}, f_{un}) , Fig. 2 , the stress-strain relationship of the unloading may be expressed as ,

$$f_c = f_{un} - \frac{f_{un} \times r}{r - 1 + x^r} \qquad (4)$$

where ,

$$r = \frac{E_u}{E_u - E_{sec}} , \quad E_{sec} = \frac{f_{un}}{\varepsilon_{un} - \varepsilon_{pL}} , \quad x = \frac{\varepsilon - \varepsilon_{un}}{\varepsilon_{PL} - \varepsilon_{un}} , \quad \varepsilon_{PL} = \varepsilon_{un} - \frac{\varepsilon_{un} - \varepsilon_a}{1 - \frac{E_c \varepsilon_a}{f_{un}}}$$

and $\varepsilon_a = a \sqrt{\varepsilon_{cc}\, \varepsilon_{un}}$, $a = 0.1175$ for plain concrete .

In which , ε_{pl} the plastic strain on the secant between ε_a and ε_{un}, ε_a the common strain at interaction of the initial tangent and the plastic unloading secant slope , Fig. 2 , and E_u the initial modulus of elasticity at the onset of unloading , which defined as , $E_u = b\, c\, E_c$, $b = f_{un} / \bar{f}_{co}$, $c = (\varepsilon_{cc} / \varepsilon_{un})^{0.5}$, $b < 1$, $c > 1$, the parameters involved in (4) were evaluated by trial using Newton-Raphson iteration to give a best fit of the assumed values.

The model expresses also the tension strength of concrete as quoted by (Mander 1984) , taking into consideration the deteriorated behaviour in tension , Fig. 2 . It was concluded from data found in literature (Sinha et al., 1964 and Mander, 1984) that the response of plain concrete in uniaxial compression under cyclic loading and the analytical model provides a good simulation of the experimental stress-strain response . So the model can be used in the present analysis with confidence .

Crak Modelling

When considering response of concrete dams to dynamic loads three different states of analyses associated with uncracked, open crack and closed crack

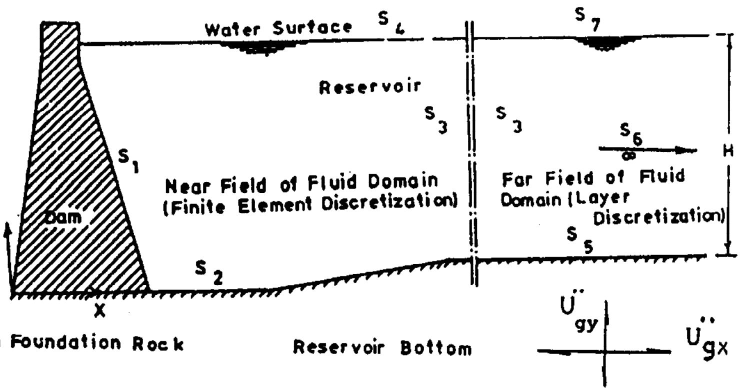


Fig. 1. Concrete Dam Reservoir Foundation System, Associated Boundaries.

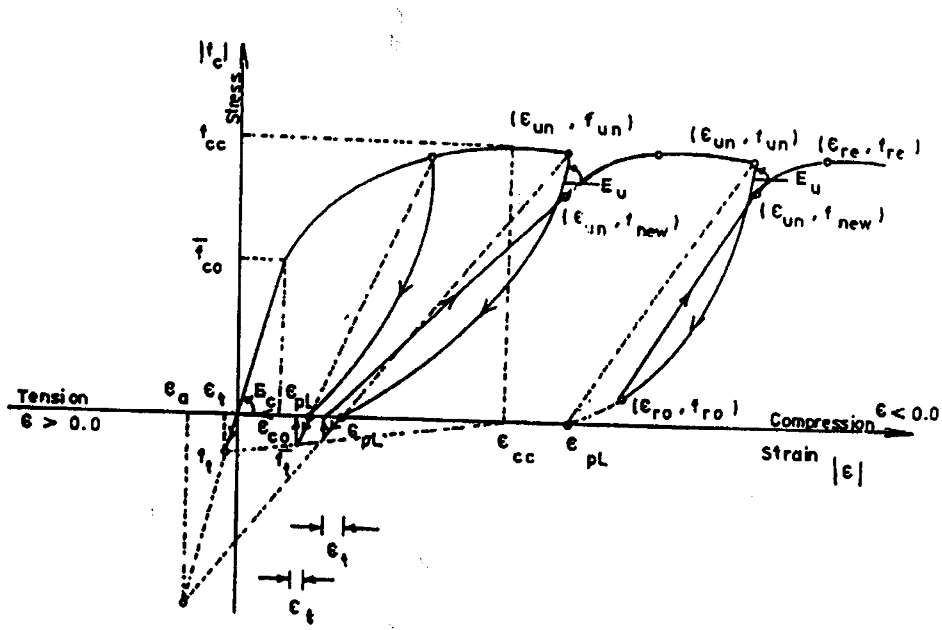


Fig. 2. Nonlinear Model of Gravity Concrete Dam Material .
(After Mander, 1984)

zones are considered in addition to the criteria of crack closure and reopening . In this study, the adopted smeared crack approach which represents the criteria of crack initiation , propagation, closure and reopening is employed as presented in study conducted by (El-Aidi, 1989). Sliding along closed crack planes is allowed according to the conventional friction concept.

EQUATION OF MOTION OF THE SYSTEM

In the present formulation, different mixed finite element approximation for displacement and pressure are adopted . Enforcing equilibrium and normal compatibility at the fluid-structure interface results in symmetric, coupled equations of motion for the system expressed as,

$$M\ddot{X} + C\dot{X} + K X + F = - M I \ddot{U}_g \qquad (5)$$

where, M , C , and F are mass , damping and vector of nonlinear forces for the coupled system , K X the vector of non linear restoring forces for the coupled system, U_g the effective earthquake acceleration due to the ground motion, I the influence matrix for the ground motion components , and X the vector of nodal relative displacements in the dam and fluid .

The restoring forces K X are partitioned into forces from dam F_D which include the effects of nonlinearity due to cracking and nonlinearity of material properties in which the stiffness K is not only amplitude but also time history dependent , and forces from the fluid F_F which include the water cavitation effects . Damping force of dam has been considered as stiffness proportional damping provides a critical viscous damping ratio for the fundamental vibration mode of the dam alone without cracking , and the damping forces are then computed as proportional to the tangent stiffness matrix for dam .

The response of the system is evaluated at successive increments Δt of time which should be chosen small enough to allow an adequate definition of the forcing excitation which are assumed to vary linearly within a time step , and on the basis that the matrices K and C remain constant during the time interval Δt . The nonlinear characteristics of these coefficients are considered in the analysis by reevaluating these coefficients at the beginning of each time increment . The generalized Newmark numerical integrations algorithm (GN22) for the second degree of equations of second order , which is unconditionally stable (Zeinkiewicz and Taylar, 1991) is used to obtain the response at the end of each time interval as an initial conditions for the next time step. During the time step the forces in an element at each equilibrium iteration is computed in the following steps . At each point the incremental and current strains are computed from the incremental and current displacements . Using the incremental and current strains , the state of crack is determined and change of stresses is computed . From the change in stresses, compute the stress at the end of the iteration and integrate the stresses , over the element numerically to give the restoring force F_D . Finally, the current tangent stiffness matrix of the element is computed . A computer program named (NLDRS-C) has been coded using the proposed analytical mothod . The results presented in this paper are obtained using this program .

NUMERICAL SOLUTIONS

Some of the obtained numerical solutions considering several cases of concrete cracking are presented . The first case study was applied on the Pine Flat Dam, the aim of the present study is to compare the achieved results with the available in literature (El.Aidi , and Hall 1989) , for sake of the developed computer program verification . The planer model and finite element discretization of the dam monolith with infinite reservoir is shown in Fig. 3. Nonlinear behaviour, mainly due to tension cracks in the dam and water cavitation in reservoir is considered . The system is assumed with the same dimensions and the same properties for concrete , rock foundation and water as considered in (El-Aidi and Hall 1989) , but the effects of water at far field, at the truncated reservoir boundary , are considered in a different way using (Tasi and Lee 1991) approach in time domain . The system is subjected to El-Centro earthquake excitation forces , scaled in amplitude by 1.5 . An initial straight horizontal crack near top of the dam placed at 21.5 m below the crest , as shown in Fig. 3 was considered, with no other cracks are allowed to initiate .

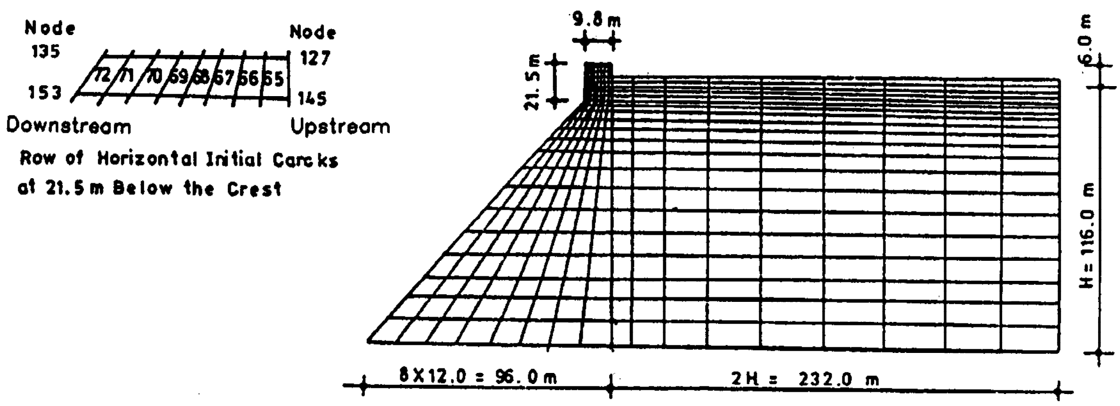
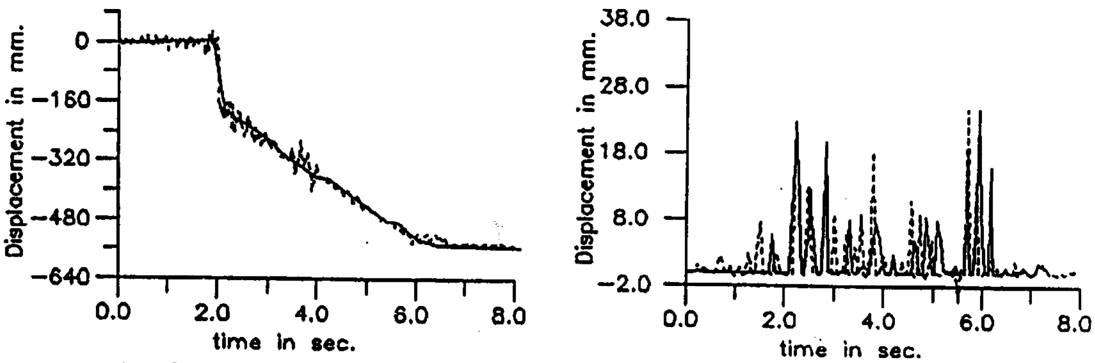


Fig. 3. Finite Element Discretization of the Pine Flat Dam-Reservoir System.

The obtained results of opening and sliding displacements of the crack were estimated . Fig. 4 shows the horizontal and vertical displacements of node 127 at the upstream face of the dam and indicates that all sliding takes place in the downstream directions and permanent slip of about 545 mm takes place , and the maximum opening displacement (vertical displacement) in the present case study is about 27 mm . The same figure (solid line) illustrates similar results but obtained by (El-Aidi, 1989) . So , one can conclude that the present result agree with the result reported by (El-Aidi, 1989) . However inadequate mesh fineness prevented an accurate assessment of this mechanism , which lead to initiation of new crack in the direction normal to the existing one , and also type of truncated vertical end zone boundary of reservoir prevented an accurate comparison with El-Aidi's results .



A. Sliding Displacement.

B. Opening Displacement

Fig. 4. Time Histories of Crack Displacements at Upstream Face (Node 127) (present study dashed lines , After El-Aidi, 1989 Solid line)

After justification of the developed computer program it is evidence now to investigated various parameters affecting the seismic behaviour of gravity concrete dam-reservoir systems .

Effect of Nonlinearity due to Material Properties

The same Dam-reservoir system is studied again but subjected to actual record of El-Centro earthquake with both horizontal and vertical ground motion without any scaling for the excitation acceleration amplitude .

Two comparative studies are conducted , in the first nonlinearity due to both concrete material and smeared cracking are considered , while in the second case study nonlinearity due to concrete cracking only are taken into considerations .The stiffness-proportional damping is removed from the element as soon as it cracked and some of the obtained results are illustrated .

Fig. 5 shows the contour of maximum principle tensile stress generated through the dam cross section in the two considered cases, which indicates that the only other large enough tension to initiate cracking still occurs at the heel of the dam. Also, by comparing the induced stresses in the two cases as shown in Fig. 5 , one can conclude that the maximum tensile stresses generated in first case study at the dam heel are about 4 % grater than stresses associated with the assumptions of the second case study , while there is no much difference between stresses in the two cases in the rest of dam cross-section.

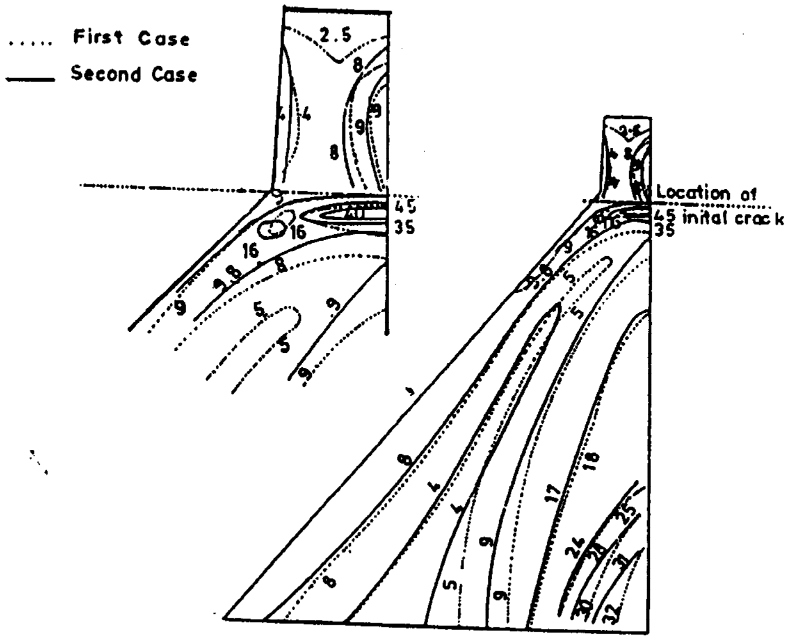


Fig. 5. Contours of the Maximum Principal Tensile stresses .
(Numbers Indicate Contour Values in Handreds of KN/m^2)

The time histories of the horizontal displacement and vertical displacements at node 127 are illustrated in Fig. 6 . By comparing the displacements response in the two cases as shown in Fig. 6 it is obvious that the permanent slip and opening in first case study is about 18.5 % and 16 % higher than predicted in the second case study . So , the assumption of linear properties of dam material employed in dynamic analysis of concrete dam-reservoir system underestimate the displacements of the detached block .

This large in the dam response with the nonlinearity of dam material , because the concrete in nonlinear analysis may suffer varying degrees of stiffness degradation due to the dynamic loading into inelastic range in addition to the decrease in stiffness coupled with cracking of the reduced , and result a sharp decrease in stiffness or slope of the load deformation curve . Unfortunately , any effect of water inflow into the crack was neglected , and open cracks were subjected to absolutely zero normal stress .

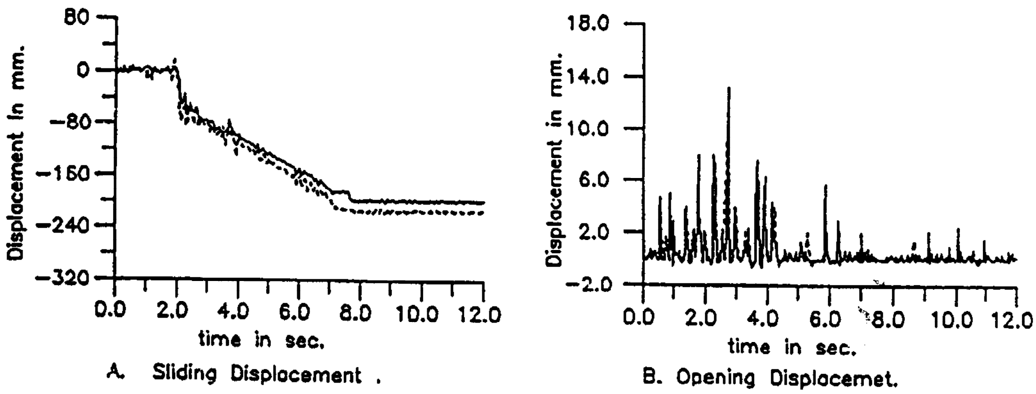


Fig. 6. Time Histories of Crack Displacements at Upstream Face (Node 127) (First case study dashed lines , Second case study Solid line)

CONCLUSIONS

From the achieved results , the developed computer program is able to compute the nonlinear response of the dam-water-foundation system under both horizontal and vertical ground motion with acceptable accuracy in time domain , where the effects of temperature and creep on the initial strains of the dam are neglected .

Including nonlinearity of concrete material into nonlinear behaviour of dam- reservoir system , causes an increases in the horizontal and vertical displacements of a detachable block , generated by cracking above the dam neck , by 18.5% and 16% respectively . Also , the maximum tensile stresses at the dam heel increases by about 4% , while there is no appreciable effects on neither the maximum tensile stresses generated on the rest of the dam section nor the hydrodynamic pressure at the dam-water interface .

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