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Seismic crack propagation in concrete gravity dams

O.A. Pekau[I] and V. Batta[II]

ABSTRACT

Crack propagation in a concrete gravity dam under seismic loading is analyzed. The boundary element method together with the principles of linear elastic fracture mechanics is employed to analyze the dynamic behaviour of a discrete crack. Propagation of the crack is monitored in a time step-by-step procedure. The formulation is employed in a study of the cracking of the Koyna dam under the 1967 Koyna earthquake, in which the effects of various parameters on the propagation process and the final crack profile are examined. The analytical results obtained appear to be in agreement with the general field observations made following the Koyna earthquake.

INTRODUCTION

Concrete gravity dams can be significantly affected by the loading produced by earthquake-induced ground shaking which may result in tensile cracking of the dam. This has been amply demonstrated by past experiences, including those of the Koyna and Hsingfengkiang dams, and also predicted by dynamic response analyses (Chopra 1987). Although these analyses identified the regions of the dam where large tensile stresses would occur, their formulations could not predict the extent of the subsequent cracking which the dam may suffer during a particular ground motion.

Prediction of the extent of a crack and its significance for the future safety of a dam poses formidable analytical difficulties. Nevertheless, the practical importance of obtaining such data to prevent catastrophic failure is becoming increasingly evident, particularly with scaling-up of the MCE for most of the existing dams. 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.

[I] Professor and Chairman, Dept. of Civil Engineering, Concordia University, Montreal, Quebec, Canada.

[II] Ph.D. student, Dept. of Civil Engineering, Concordia University, Montreal; also Structural Engineer, Shawinigan Lavalin Inc., Montreal, Quebec, Canada.

Dynamic fracture analyses generally employ either the finite element or the boundary element method to discretize the structure, together with a discrete or smeared approach to model the crack itself. However, most of the available studies have used the finite element method and, to date, the boundary element method has found only a limited application in this area. The available finite element procedures are those by Graves and Derucher(1987) and Mlakar(1987), who used a smeared crack approach to study the developement of tensile cracks in concrete gravity dams subjected to ground motion. While the model used by Graves and Derucher was limited to small cracks only, Mlakar used three different examples of dams in the United States to show that, under a strong earthquake, cracks may penetrate the entire cross-section of a dam. However, the geometry (length and width) as well as the exact location of these cracks could not be obtained from the analysis because of the use of the smeared crack approach in the formulation.

The discrete crack approach, on the other hand, not only has the potential of determining the above characteristics but is also more suited to model the physical behaviour of unreinforced concrete during and after cracking. This is because the concrete would develop a distributed (smeared) cracking pattern only if reinforcing steel is present. Employing discrete cracks, Skrikerud and Bachmann(1986) and Saouma et al(1990) have recently presented finite element analyses of concrete dam cracking. However, in spite of a correct physical representation of the crack these studies still require the redefinition of the finite elements in the vicinity of the crack tip. Moreover, as shown by Skrikerud and Bachmann(1986), the predicted crack pattern is extremely sensitive to the nodal density of the finite element mesh. Recently, for a propagating discrete crack in concrete dams, Pekau et al(1991) have presented a methodology employing the boundary element technique together with the discrete crack approach. In this study the dynamic response was obtained by the mode superposition technique and the nonlinear crack-closing behaviour was modelled using load pulses.

PRESENT FORMULATION

In the present study the frequency independent dynamic boundary integral formulation, presented by Nardini and Brebbia(1982), is employed. Isoparametric boundary elements are used for the discretization of the structure which is divided into subdomains in such a way that the two crack flanks belong to adjacent domains (Blandford et al 1981). This procedure, known as the multidomain discretization scheme, provides a mathematically correct crack representation and allows for the subsequent stress intensity factor computations using the displacement correlation technique. Analytical singularities exhibited by tractions in front of the crack tip are accounted for by using traction singular quarter-point elements. The latter are obtained by a suitable transformation of the isoparametric boundary elements.

Using the above discretization scheme, boundary integrals for each subdomain are evaluated and the governing equations of dynamic equilibrium are assembled. A time step-by-step solution of these equations is obtained by direct integration. Time integration using the Houbolt method is employed in the present study because the method is unconditionally stable and provides numerical damping for higher modes.

Dynamic fracture analysis

Dynamic analysis of a structure with discrete crack and subjected to an oscillatory time-dependent loading, as imposed by an earthquake, also requires additional analytical modelling of the crack closing behaviour. This is because, when the crack closes, the crack flank nodes in the analytical model tend to overlap, which is inconsitent with the true physical behaviour. Thus, while an open crack is accurately represented in the model, the crack closure is modelled by introducing dimensionless springs between the nodes on the crack surfaces. During the subsequent opening phase these springs are removed and the structural stiffness is appropriately modified to once again obtain traction free crack surfaces. The stress intensity factors are obtained from the crack flank displacement data and the maximum tensile strain theory (Pekau et al 1991) is used to determine the direction and times of propagation of the discrete crack.

PARAMETRIC INVESTIGATION

Various parameters which generally influence the seismic behaviour of concrete gravity dams comprise the presence of gravity loads, reservoir interaction, foundation interaction, reservoir bottom absorption and the direction in which the earthquake loading is applied. In addition, the value of the dynamic fracture toughness for concrete and the length by which the discrete crack is extended at each stage of crack propagation also have a very significant influence on the resulting crack profile. It should be noted that the selection of the length of crack extension is a limitation of all discrete crack formulations. While a large value of the extension may result in forcing the crack profile in a certain direction, too small an extension would, on the other hand, be numerically inefficient.

Although a number of the above effects were considered in this study, results are presented here for only a few of these parameters. For the example application which follows, two different parametric cases were defined. In Case 1, the gravity loads due to the weight of the concrete as well as the effect of the reservoir were not considered. The earthquake loading was applied in both the horizontal and vertical directions and the influence of the length of the piecewise crack extension on the computed crack profile was studied. In Case 2, the gravity loads were included and the analysis was conducted for a full reservoir. Thus, both the hydrostatic as well as the hydrodynamic interaction of the impounded water were incorporated in the dynamic analysis. The latter was modelled as an added mass considering the water as incompressible. In this case also, the ground motion was applied in both directions. The dam was considered fixed at the base in both cases and the effect of reservoir bottom absorption was not included.

DISCUSSION OF RESULTS

Using the procedure presented in this paper, a parametric dynamic fracture analysis of the Koyna dam subjected to the Koyna earthquke of Dec. 11, 1967 was conducted. Since the ground motion of the Koyna earthquake was recorded by a series of strong motion accelerographs located in a gallery close to the foundation of the dam, relevant comparison between analytical results and the observed behaviour can also be drawn.

The Koyna dam is 854 m long and 103 m high at the tallest non-overflow monolith and has a cross-section which is not typical of a gravity dam (see Fig. 1). As shown in Fig. 2, cracking of the dam during the Koyna earthquake resulted in roughly horizontal cracks on both the upstream and downstream faces near elevation 66.5 m and there was inconclusive evidence that some of these cracks might have penetrated through the entire width of the dam. Based on this observation, an initial crack 1.0 m in length was assumed in the present analysis at elevation 66.5 m. on the downstream face of the dam. Occurrence of crack initiation on the downstream face was also predicted by Chopra(1987). The boundary element discretization employed for the cracked dam is shown in Fig. 1.

Linear elastic material properties, valid for the entire cross-section, were used for the concrete: modulus of elasticity = $31\text{x}10^3$ MPa, Poisson's ratio = 0.2 and mass density = 2400 kg/m^3. Damping equal to 5% of critical was assumed in the first two modes of vibration. The dynamic fracture toughness for concrete was assumed to be 1.96 $MPa.m^{1/2}$.

Figures 3(a) and 3(b) show the time histories of horizontal displacement and acceleration at the dam crest for Case 1. Corresponding plots of stress intensity factors are shown in Figs. 4(a) and 4(b). Fig. 5 shows the computed crack profile for this case. The crack profile is shown for two different values of the assumed crack extension lengths, namely 0.5 m and 1.0 m. As evident in Fig. 5, almost identical profiles are predicted for the two extension lengths. A piecewise extension of 1.0 m was thus used in the subsequent analyses.

The response results for Case 2 are presented in Figs. 6(a) and 6(b), while Figs. 7(a) and 7(b) depict the computed stress intensity factors for this case. From Fig. 7(a), it can be seen that the gravity loads of the present case oppose opening of the crack, which remains closed until approximately 1.95 sec, at which time the first major peak of ground acceleration occurs. This is unlike Case 1, where the crack opens and closes a number of times before finally breaking through to the opposite face of the dam at 1.95 sec. The predicted crack profile for Case 2 is shown in Fig. 8. It can be seen that the crack penetrates through the entire width of the dam and reaches the upstream face near elevation 65.0 m which is consistent with the observed behaviour. Furthermore, compared to Case 1 (no static loads), the profile of Case 2 shows that inclusion of these forces does not have a profound influence on the final pattern of cracking for the Koyna dam. Rather, static loads affect primarily the times at which the crack is induced to propagate during seismic excitation. This was evident from the previous comparison of Figs. 4 and 7.

FINAL REMARKS

Based on the results of this study, it appears that the present boundary element formulation is well suited for the dynamic crack propagation analysis of mass concrete structures such as gravity dams. Moreover, various analytical and physical parameters affect the pattern of the predicted cracking. These involve primarily the fracture toughness of concrete, the assumed length of the incremental crack extensions and the loading conditions of the dam.

REFERENCES

Blandford, G.E., Ingraffea, A.R. and Ligget, J.A. 1981. Two-dimensional stress intensity factor computations using the boundary element method, International Journal for Numerical Methods in Engineering, 17, 387-404.

Chopra, A.K. 1987. Earthquake analysis, design and safety evaluation of concrete dams, 5th Canadian Conference on Earthquake Engineering, 39-62.

Graves, R.H. and Derucher, K.N. 1987. Interface smeared crack model analysis of concrete dams in earthquakes, Journal of Engineering Mechanics Division, ASCE, 113(11), 1678-1693.

Mlakar, P.F. 1987. Nonlinear response of concrete gravity dams to strong earthquake-induced ground motion, International Journal of Computers and Structures, 26(1/2), 165-173.

Nardini, D. and Brebbia, C.A. 1982. A new approach to free vibration analysis using boundary elements, 4th International Conference on Boundary Element Methods, Springer Verlag, Berlin, 312-326.

Pekau, O.A., Zhang, C. and Feng, L. Seismic fracture analysis of concrete gravity dams, Accepted for publication in Earthquake Engineering and Structural Dynamics

Saouma, V.E., Bruhwiler, E. and Boggs, H.L. 1990. A review of fracture mechanics applied to concrete dams, Dam Engineering, 1, 41-57.

Skrikerud, P.E. and Bachmann, H. 1986. Discrete crack modelling for dynamically loaded, unreinforced concrete structures, Earthquake Engineering and Structural Dynamics, 14, 297-315.

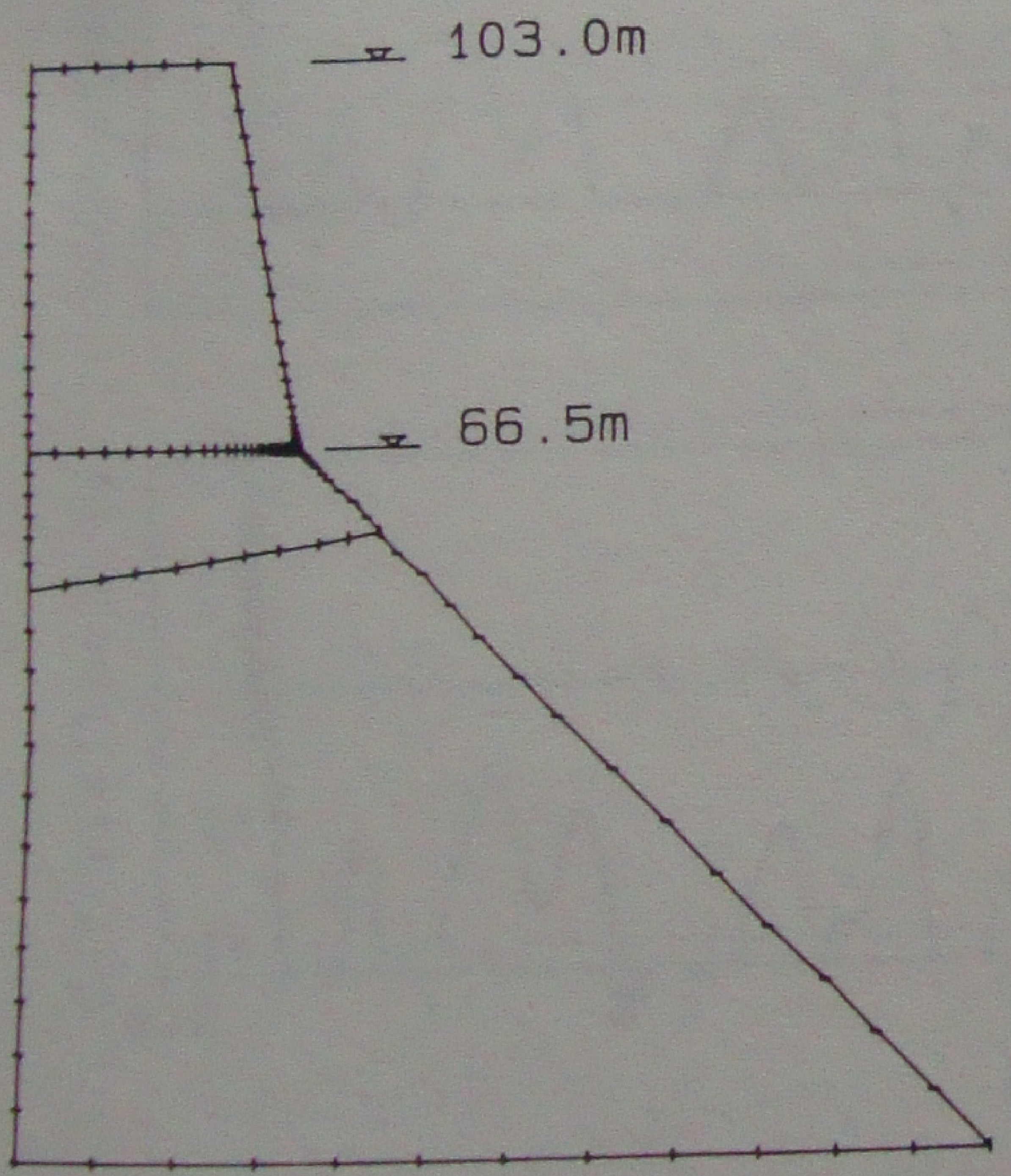

Figure 1. Koyna dam and BE mesh

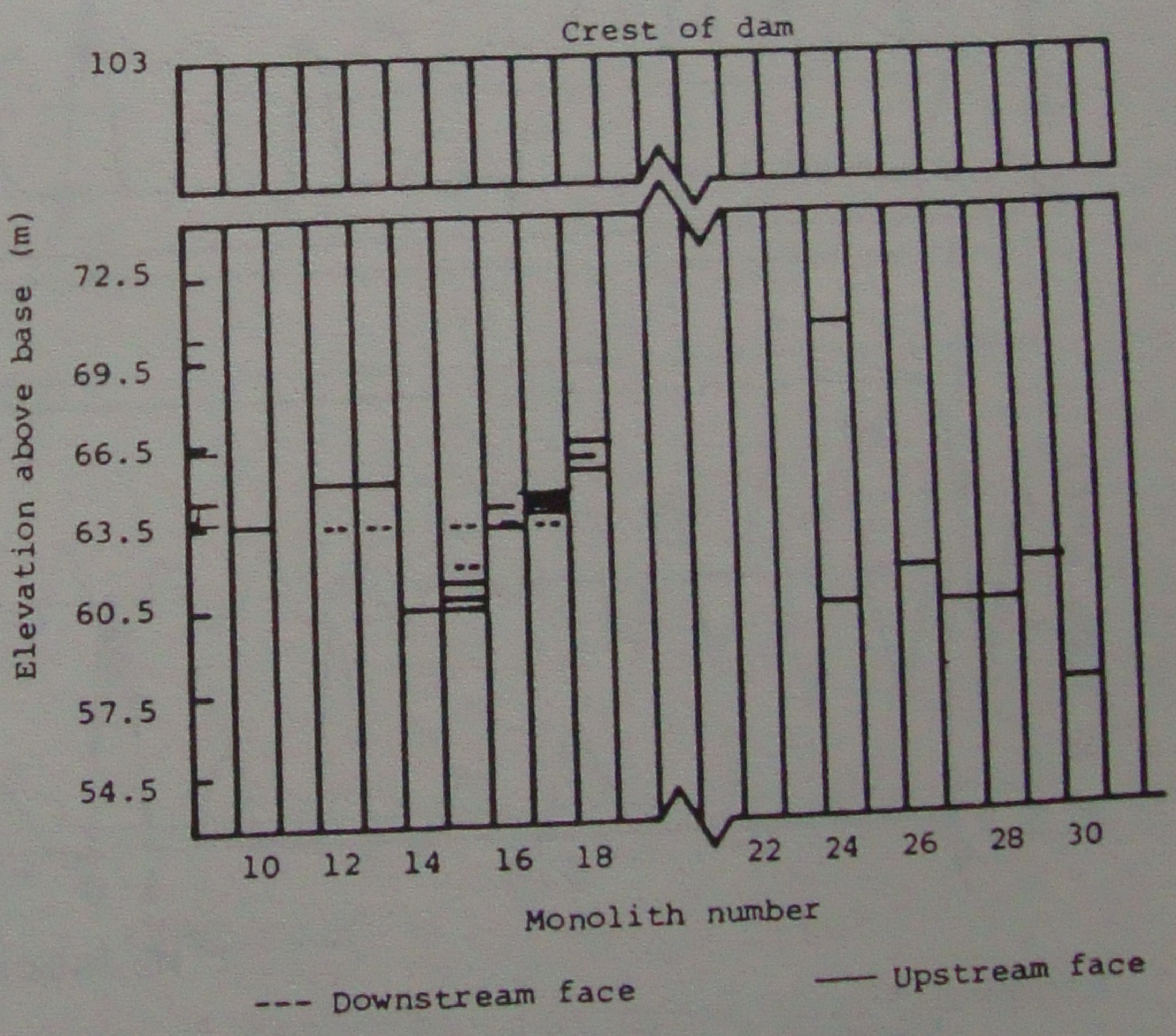

Figure 2. Observed pattern of cracking in Koyna dam

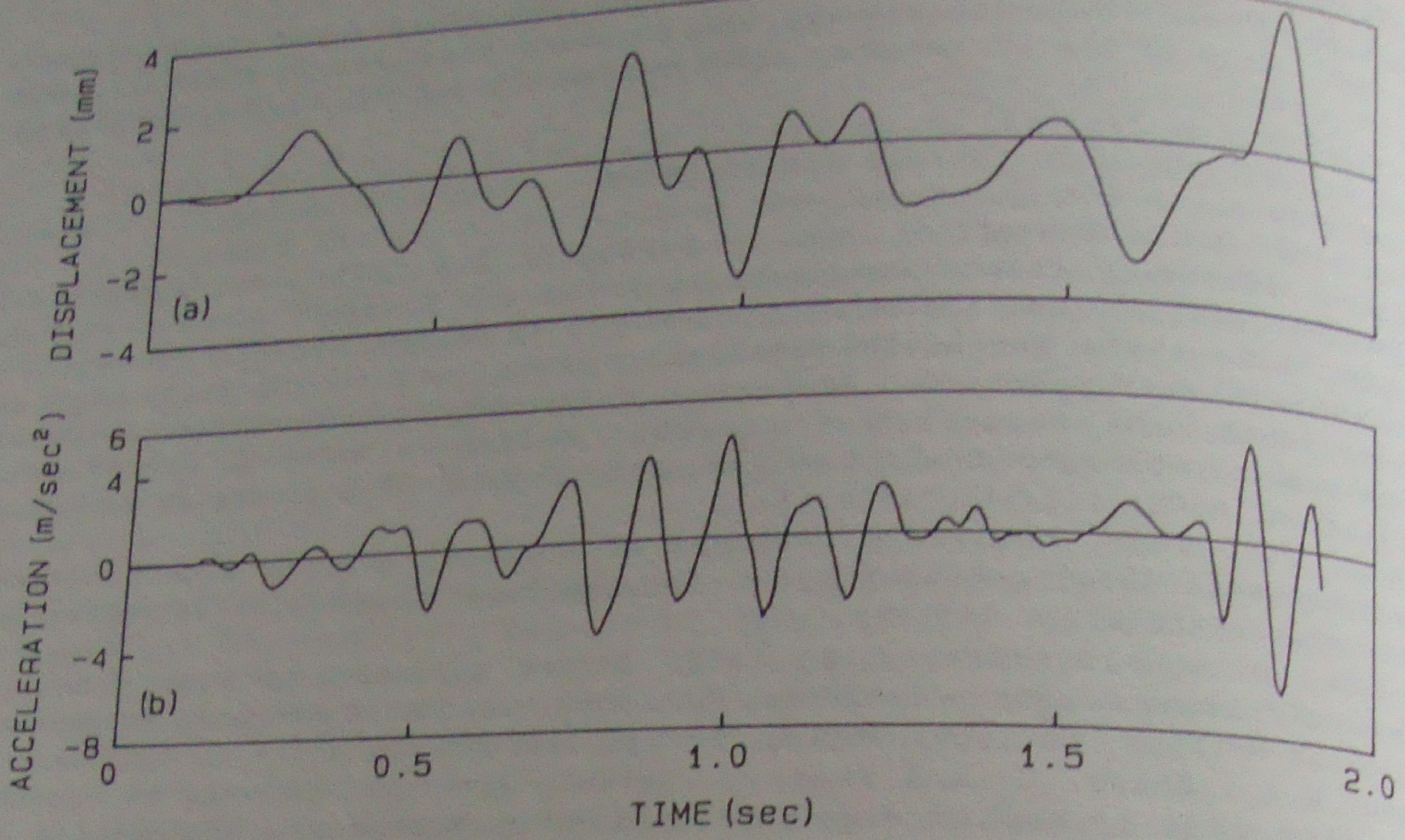

Figure 3. Case 1 time histories of response: (a) crest displacement; (b) crest acceleration

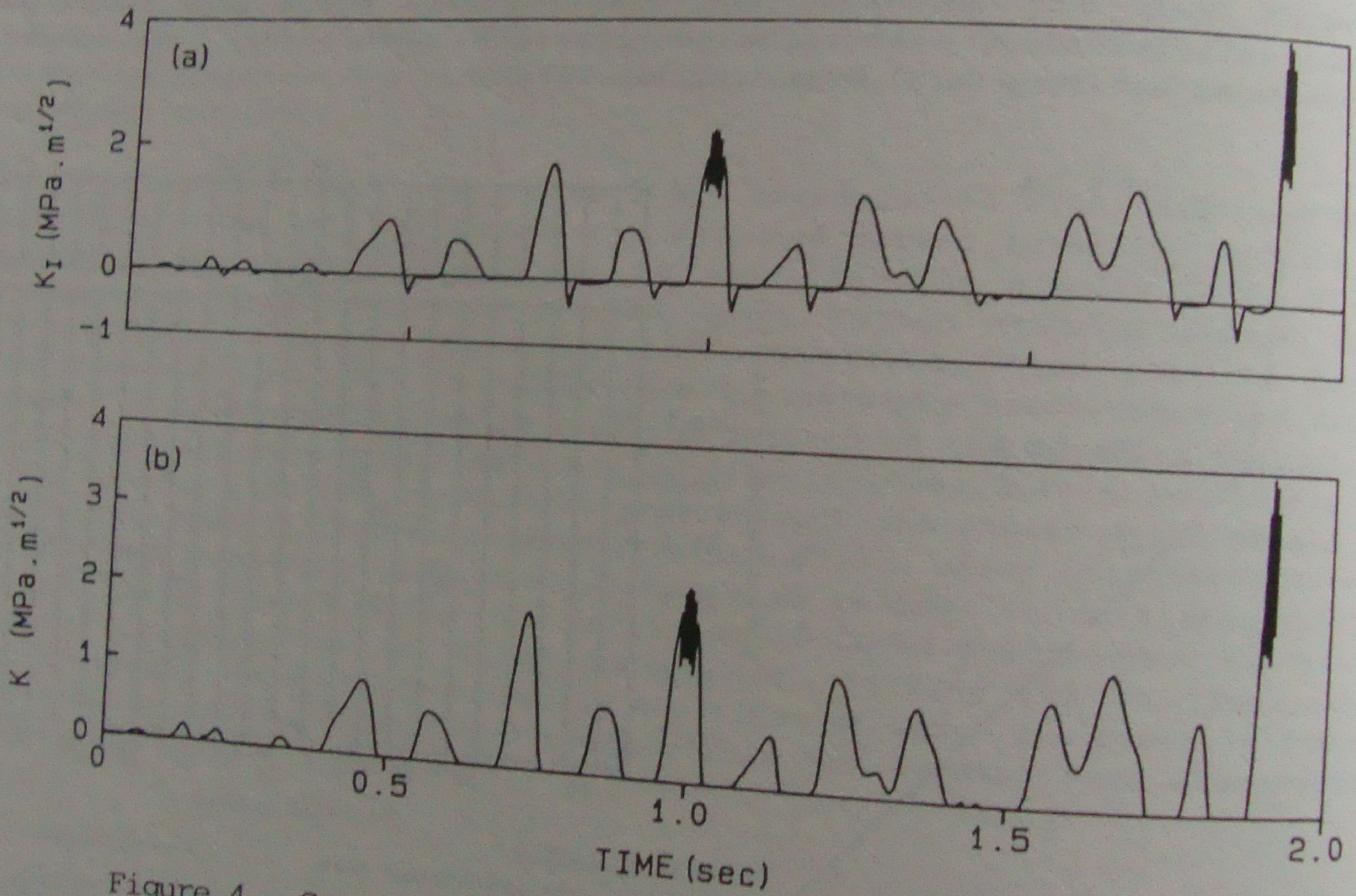

Figure 4. Case 1 time histories of stress intensity factors: (a) crack opening mechanism; (b) combined opening and sliding mechanism

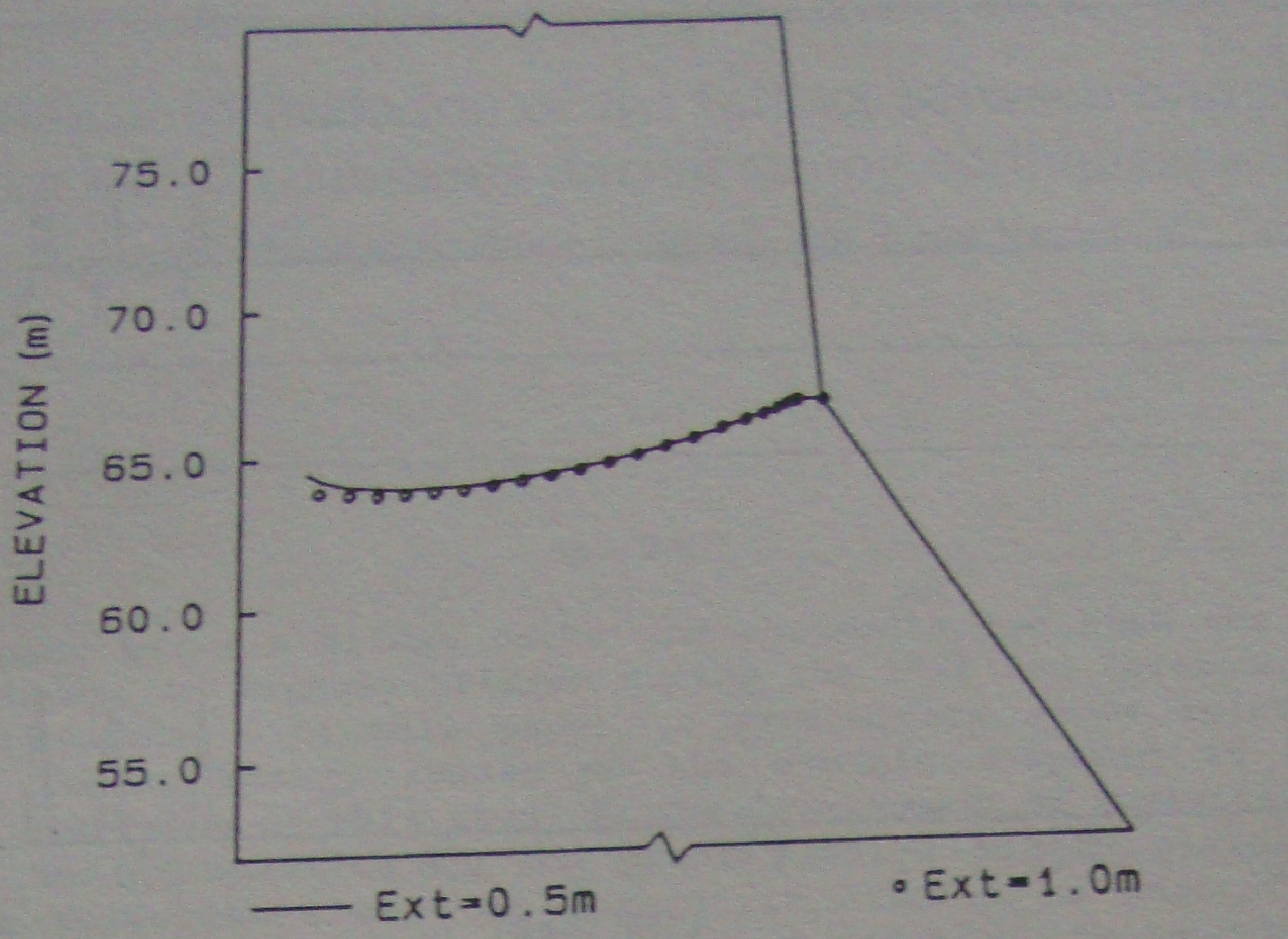

Figure 5. Effect of crack extension length on crack profile

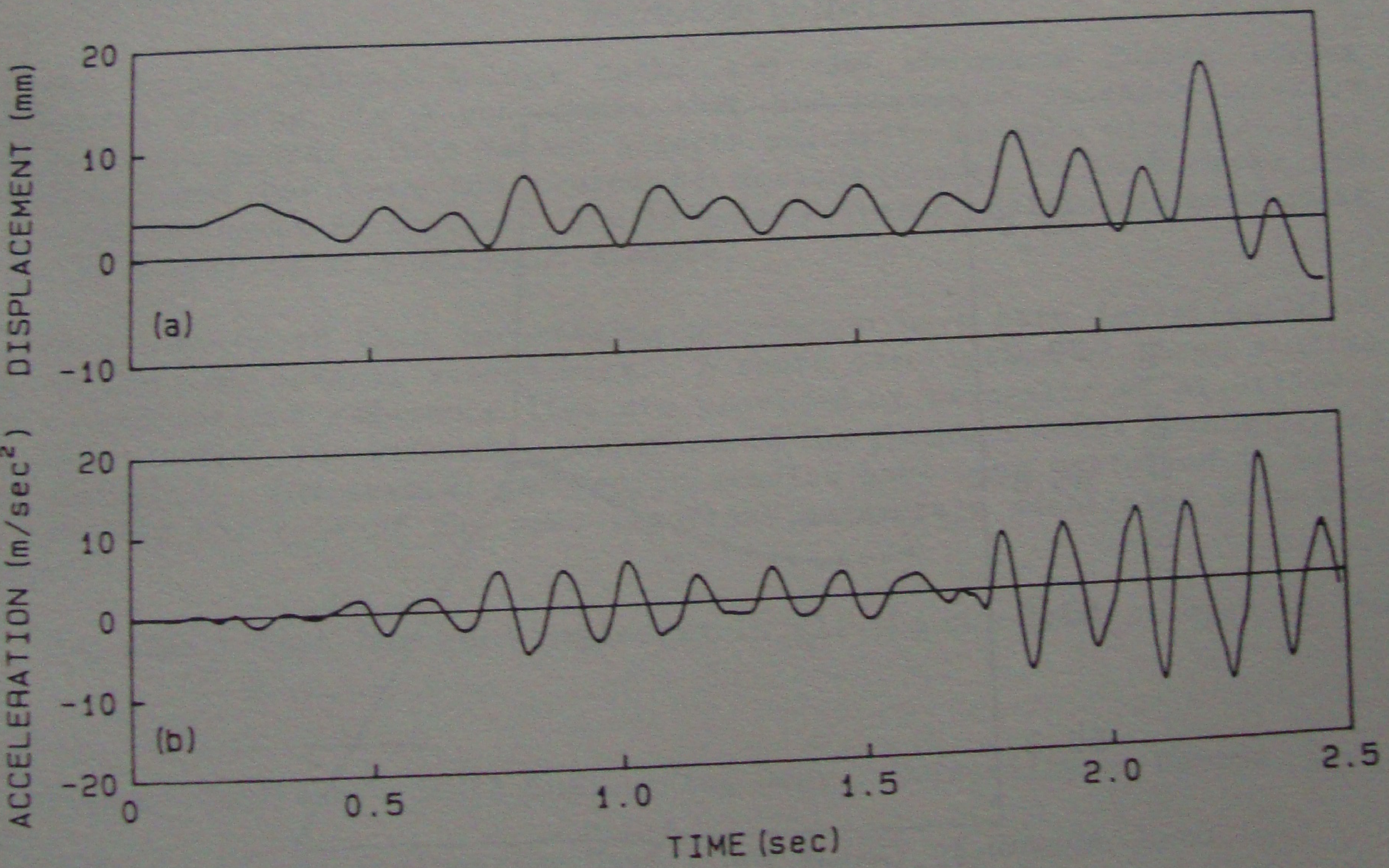

Figure 6. Case 2 time histories of response: (a) crest displacements; (b) crest acceleration

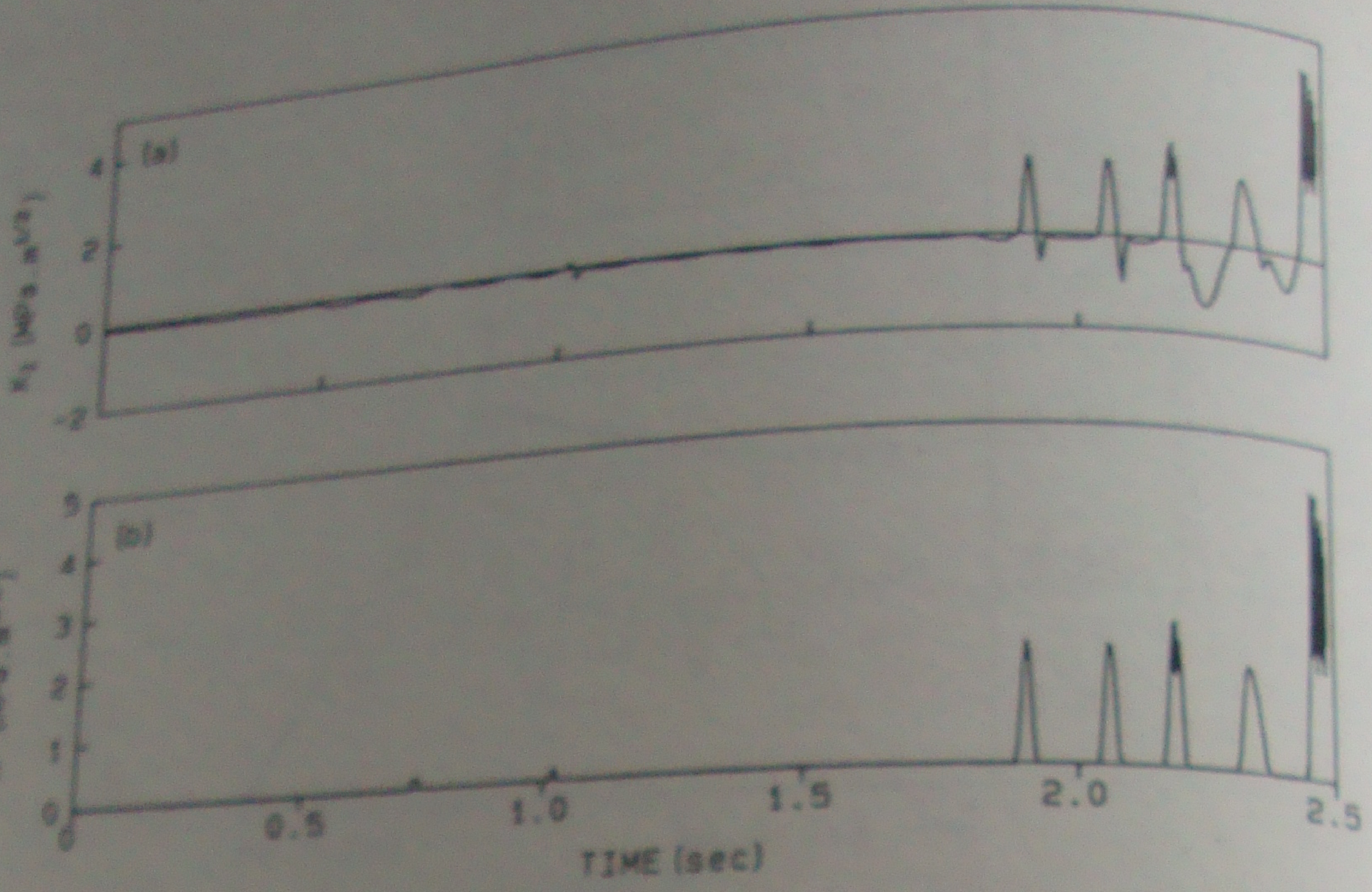

Figure 7. Case 2 time histories of stress intensity factors: (a) crack opening mechanism; (b) combined opening and sliding mechanism

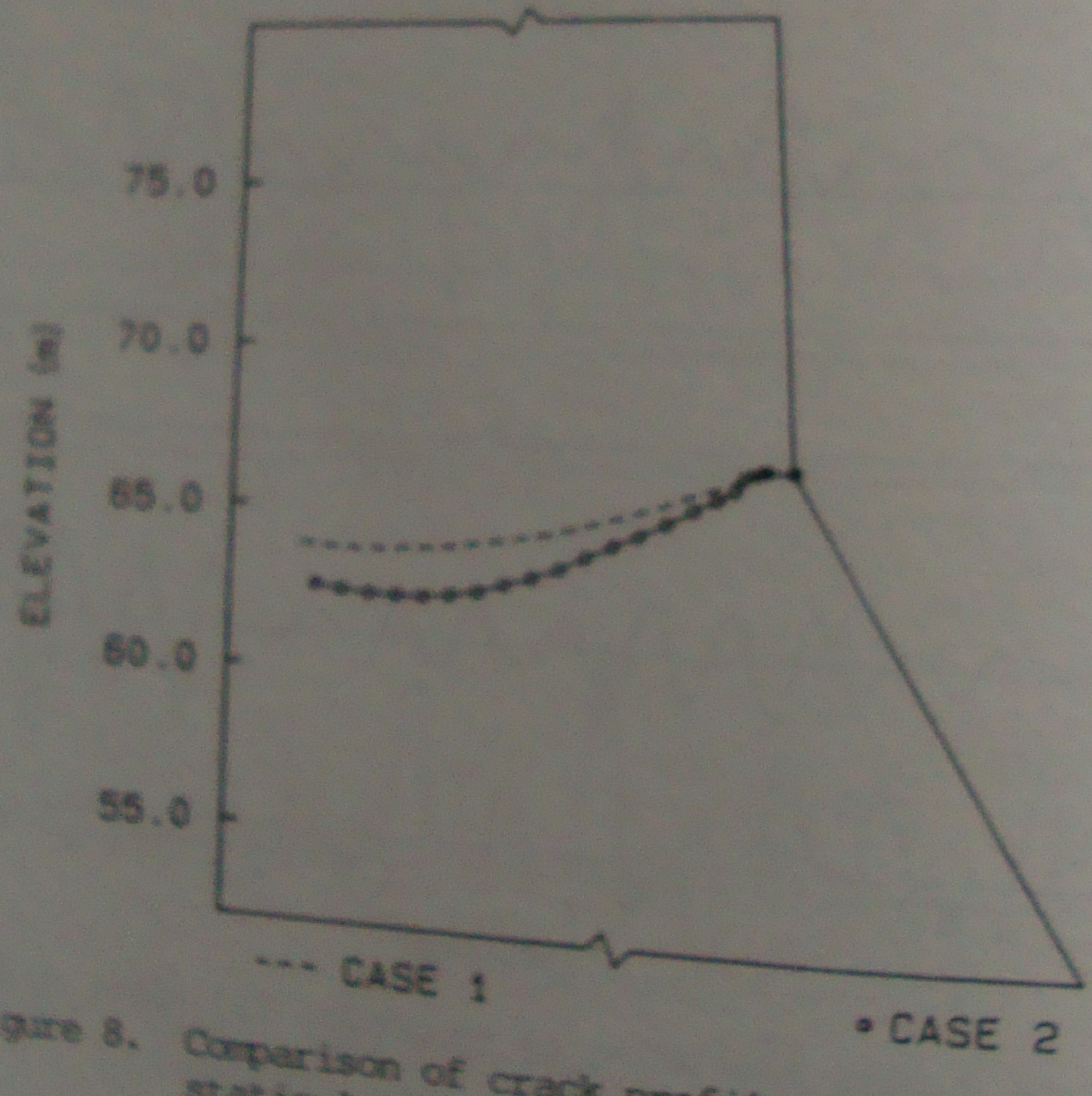

Figure 8. Comparison of crack profiles for: Case 1 - no static loads; Case 2 - static loads included