Nonlinear Rock Mechanics Analysis of Gravity Dams under Combined Flood and Earthquake Loading

by

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ABSTRACT

The two-dimensional nonlinear incremental response of a gravity dam subjected to earthquake loading is outlined. The dam is assumed to stand on jointed rock and to be impounding a full-reservoir upstream water level. The material constitutive relations for rock discontinuity are expressed in terms of an incremental plasticity model that fully represents the coupling between joint normal and shear deformations due to dilatancy. The model also accounts for stiffness degradation of joints upon wear and shear distortion, and for the bulking/seating effects of separated rock debris. The instantaneous center of rigidity and the associated principal directions of rigidity for the dam-rock system are located analytically for each step of the load history, and the displacement and force responses of the rock joint elements are obtained incrementally. Results are compared to those from corresponding finite-element analyses.

KEYWORDS: Bottom-absorption hydrodynamic force spectra; finite-element modeling; flood; nonlinear earthquake analysis; rock mechanics.

1. INTRODUCTION

In order to build the model in this investigation, several recent studies dealing with the behavior of rock discontinuities under shear and normal loading were examined. Saeb and Amadei (1992) developed a tangent formulation for the deformability of a rock joint that fully accounts for the coupling between joint normal and shear responses due to dilatancy. Plesha (1987) and Qiu et al. (1993) have developed a macroscopic constitutive law for initially closely mated joints undergoing small displacements that includes dilatancy, damage of surface roughness, and cyclic sliding behavior in the light of the theory of plasticity. This theoretical model was experimentally verified for simple laboratory experiments on both natural and artificial rock joints (Huang et al. 1993). Mroz and Giambanco (1996) developed an interface constitutive model accounting for slip and sliding effects. The microslip effects were described by considering the interaction between asperities modeled as spheres in contact by appealing to the generation of progressive or reverse slip zones.

The constitutive law for rock discontinuities applied in this investigation mirrors Plesha's model (See de Béjar, L.A. & S. Garner 1998). Associated-flow plasticity was adopted because it results in symmetric stiffness matrices that dramatically simplify the ensuing numerical analysis procedures. Joint asperities are modeled as harmonic elements in regular array, starting from the fresh-joint perfectly mating configuration. Degradation is modeled in terms of an exponential decay of inclination with respect to the initial overall joint plane, as a function of the cumulative plastic work on the asperities. Bulking/seating effects are built into the normality rule and subsequently into the consistency condition of the theory. Bulking effects may be disregarded for monotonically increasing load but must be included in the formulation for problems involving reversal of frictional shear in the case

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of earthquake loading.

2. MODELING THE DAM-FOUNDATION ROCK SYSTEM

The dam-parent rock system is idealized as a rigid body standing on a set of elasto-plastic rock discontinuities (Figure 1). The surface of contact of the rock discontinuities is idealized as sinusoidal (Figure 2). This assumption allows easy calculation of the displaced configuration as mating blocks friction slide and climb on each other during dynamic response. Each discontinuity resists normal and tangential forces through stiffnesses that evolve as the exciting load fluctuates in magnitude (Figure 3). The instantaneous center of rigidity and the associated principal directions of rigidity for the dam-rock system are located analytically for each step of the load history (Ayre 1938, de Béjar 1985). The model includes the hydrodynamic pressure field on the upstream face of the dam, effective upon bottom absorption of seismic energy in the reservoir. The model also includes the effects of a downstream pool and the resultant uplift forces exerted by the pore water pressure field within the rock joints on the upper discontinuity surfaces. This last effect varies continuously as the dam-foundation rock system translates and rotates during the response history.

3. ELASTO-PLASTIC CONSTITUTIVE LAW FOR ROCK DISCONTINUITIES

In this model, stresses are assumed uniformly distributed over each segmental rock joint; however, there is no limit as to the number of joints to be considered in a given problem. The Coulomb dry friction slip criterion is taken as the slip surface to signal the onset of plastic flow in rock discontinuities, and is given by (Qiu et al. 1993):

$$\begin{aligned} F(\{f\},\alpha) &= |f_t \cdot \cos\alpha + f_n \cdot \sin\alpha| + \\ &+ \mu \cdot (-f_t \cdot \sin\alpha + f_n \cdot \cos\alpha) = 0 \end{aligned} \qquad (1)$$

where $\{f\} = \langle f_t \; f_n \rangle^T$ = vector of internal forces on the rock joint, α = the instantaneous tangential inclination of the point of contact between lower and upper faces of a joint asperity, and μ = static coefficient of dry friction for the rock joint. The same function $F(\{f\}, \alpha)$ is specified as the plastic deformation potential leading to associated flow. The formulation of the theory of plasticity leads to an explicit relation between the increment of displacement and the corresponding increment of internal force, which may be written as:

$$\{df\} = \begin{cases} [E] \cdot \{dg\} & , F<0 \text{ or } dF<0 \\ [E^*] \cdot \{dg\} & , F=0 \text{ and } dF=0 \end{cases} \qquad (2)$$

where $[E]$ = Elastic stiffness matrix (diagonal) for the rock discontinuity, and
$[E^*]$ = Elasto-plastic stiffness matrix (fully populated and symmetrical).

4. NUMERICAL ANALYSIS

The two-dimensional response of the gravity dam standing on jointed rock is calculated incrementally. At each step in the analysis, the incremental displacement response of the system is obtained after adjusting the material state (elastic/plastic) of all joints for consistency with their corresponding states at the end of the step. If, during the analysis for a given step, lack of consistency is detected between the initial and the final states of any joint in the set, the analysis is repeated altogether for the step, using half the current value of the time step.

The incremental response for a given step is obtained as the summation of partial contributions obtained from successive attempts to restore dynamic equilibrium under the effective earthquake forces, which include both the inertial and structural damping components. At each attempt, the partial response of the system is obtained using its current stiffness matrix at the beginning of the step and the principal rigidity properties for the system, obtained from the elements as if their normal and tangential actions were uncoupled. This process is graphically illustrated by the flow diagram in Figure 4 (for the one-dimensional case), in which ($\{f\},\{\delta\}$) and ($\{F\},\{\Delta\}$) are the effective earthquake force and displacement response pairs for the joints and the system, respectively (Quantities for the system are referred to the principal rigidity coordinates attached to the center of rigidity).

As a simple example of application, Figure 5 shows an idealized dam-rock system under a comprehensive representation of the equilibrating forces during earthquake response. The hydrodynamic pressure field D in this representation is effective, after bottom-absorption effects have been estimated from previous studies (de Béjar, L.A. 2000).

Figure 6 shows a typical set of hydrodynamic force spectra normalized with respect to the corresponding scaled hydrostatic resultant force on the upstream face of the dam, for various degrees of elasticity of the underlying supporting rock (represented by the coefficient of reflection α), and developed for the San Fernando earthquake of Feb. 9, 1971. Figure 7 shows the distribution of the shell major principal stresses of the system standing on nonlinear gap elements simulating the rock discontinuities. An extreme-load scenario of simultaneous flood-earthquake excitation has been assumed to emphasize the detrimental effects on the system under such conditions. The results of the analysis using the rigid-body engineering model are contrasted with those from the finite-element formulation for comparison.

5. SUMMARY

An engineering model for the nonlinear behavior of rock discontinuities under concrete gravity dams subjected simultaneously to flood and earthquake has been outlined. The material representation for rock joints had been previously verified in closely controlled laboratory experiments. The resulting computer capability is intended to examine effectively the progression of damage associated with specific states for concrete gravity dams during earthquake response. In particular, the model will assist in the definition of limit states and the construction of fragility curves for comprehensive risk analyses (de Béjar, L.A. 1999).

6. ACKNOWLEDGMENTS

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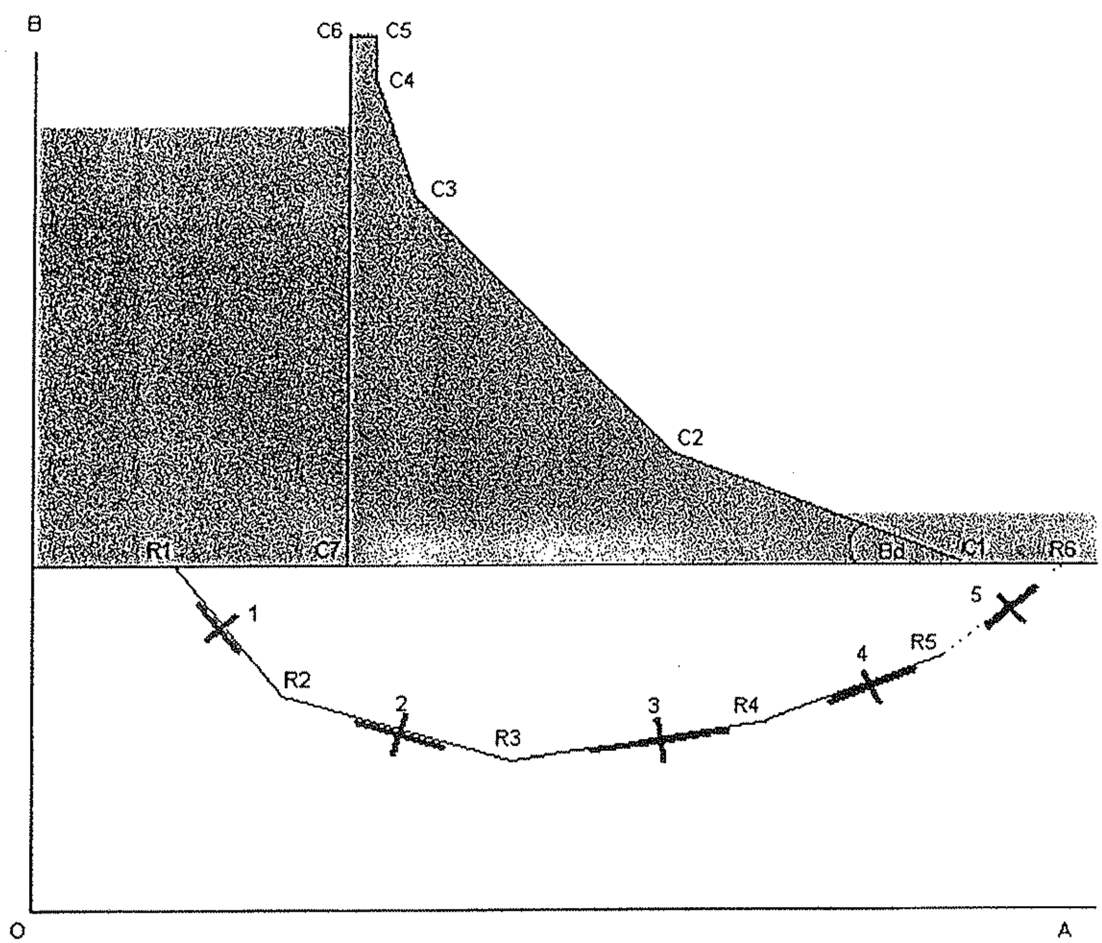

FIGURE 1. Analytical model for dam-rock-discontinuities system

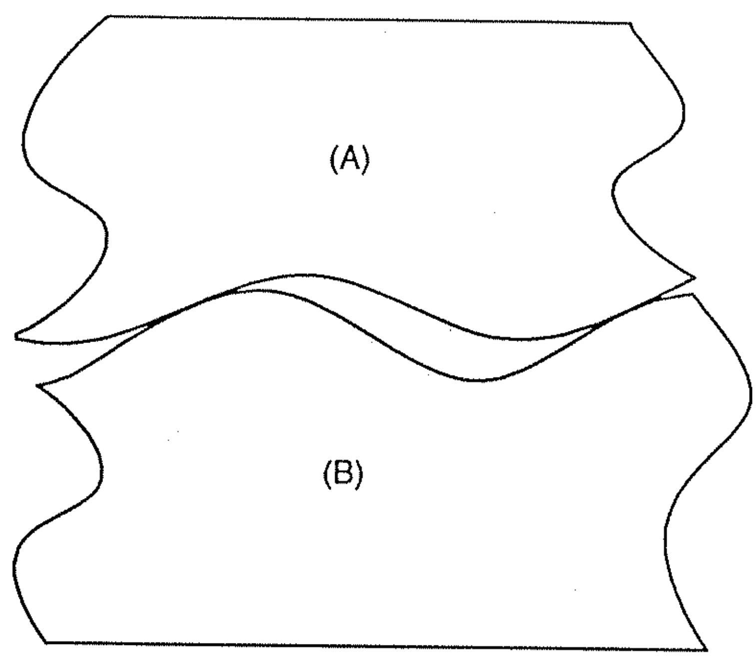

FIGURE 2. Idealization of asperity contact in rock discontinuity friction sliding

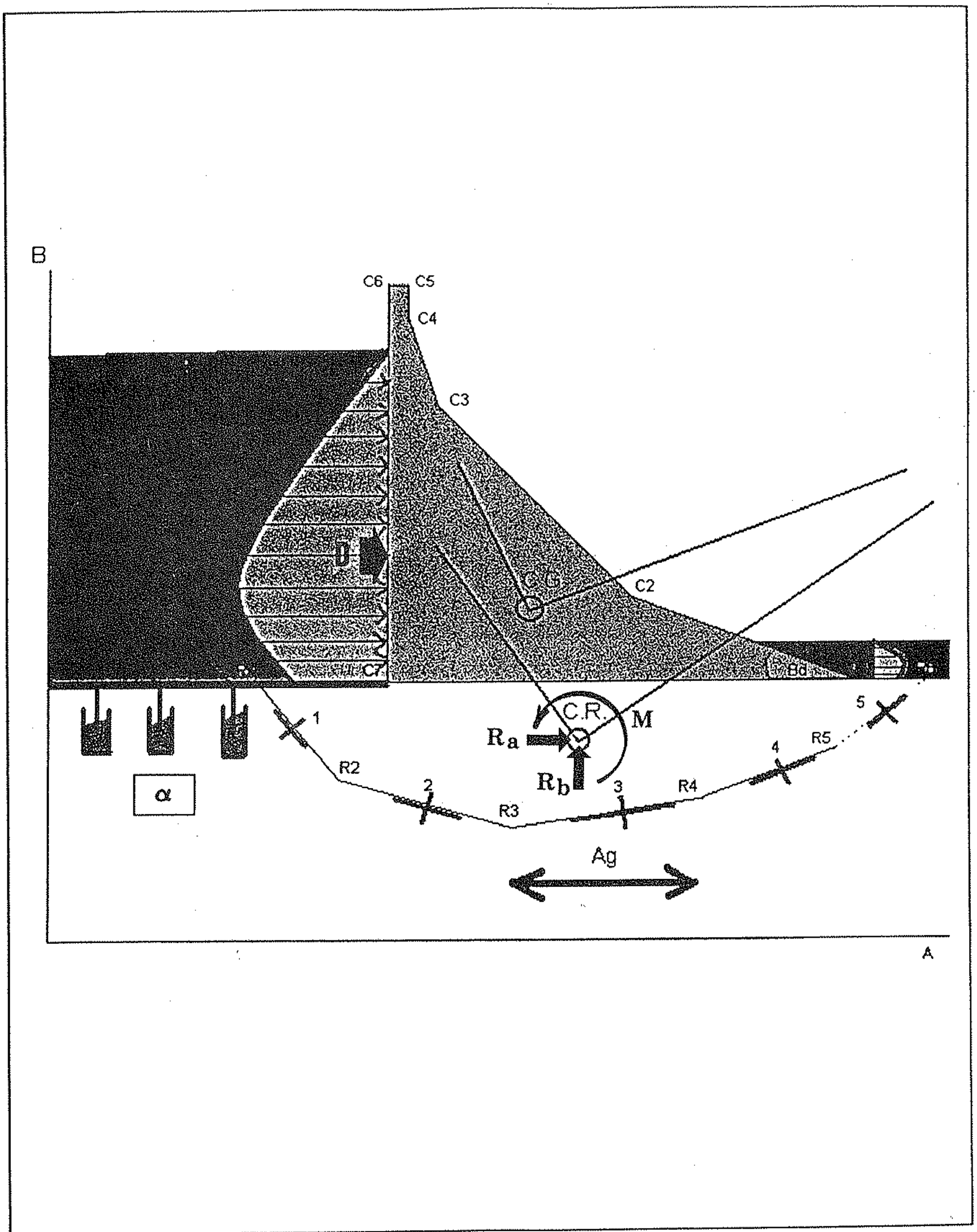

FIGURE 3. Analytical model for the dam-system components under earthquake

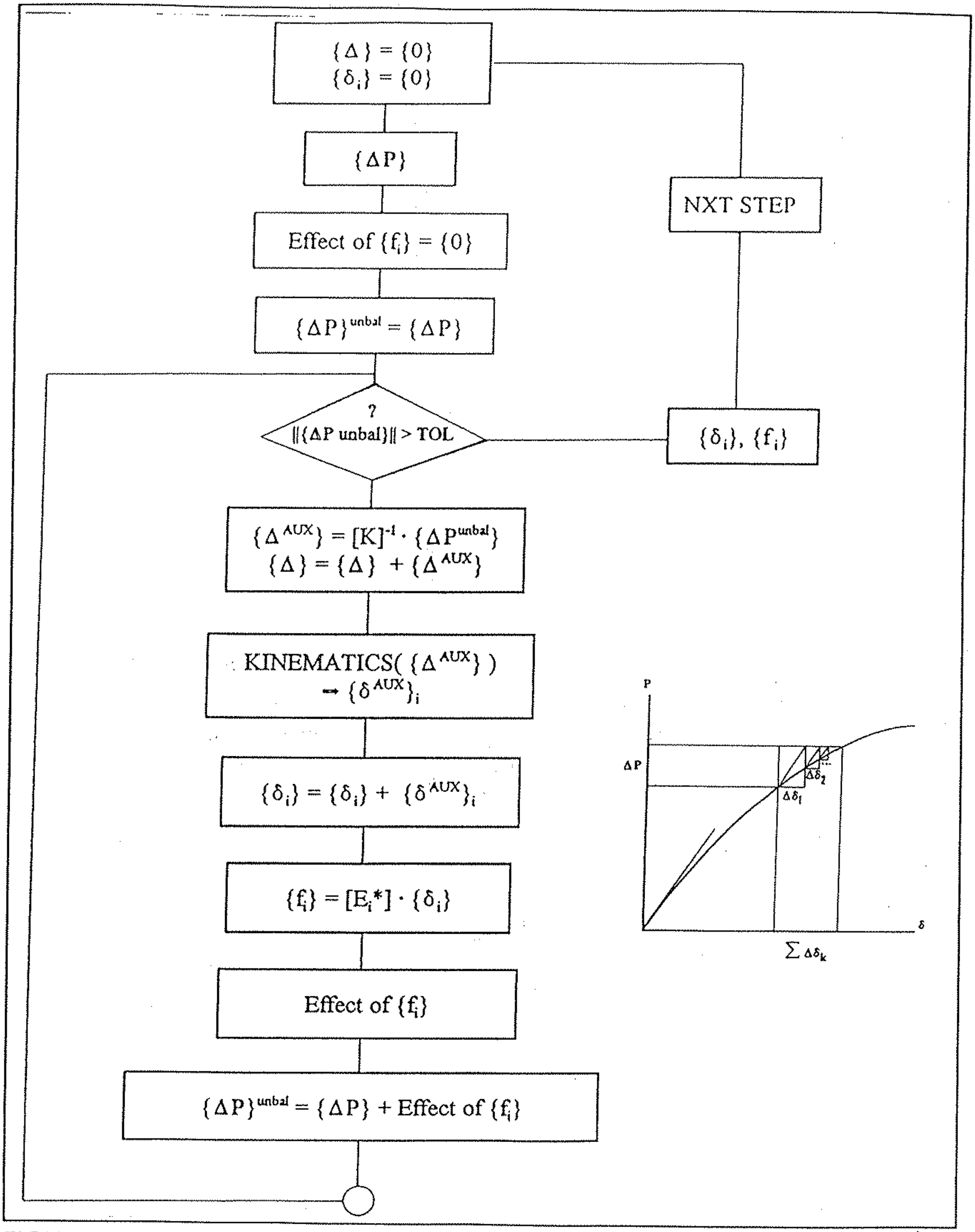

FIGURE 4. Global flow of numerical iterations within a given load step

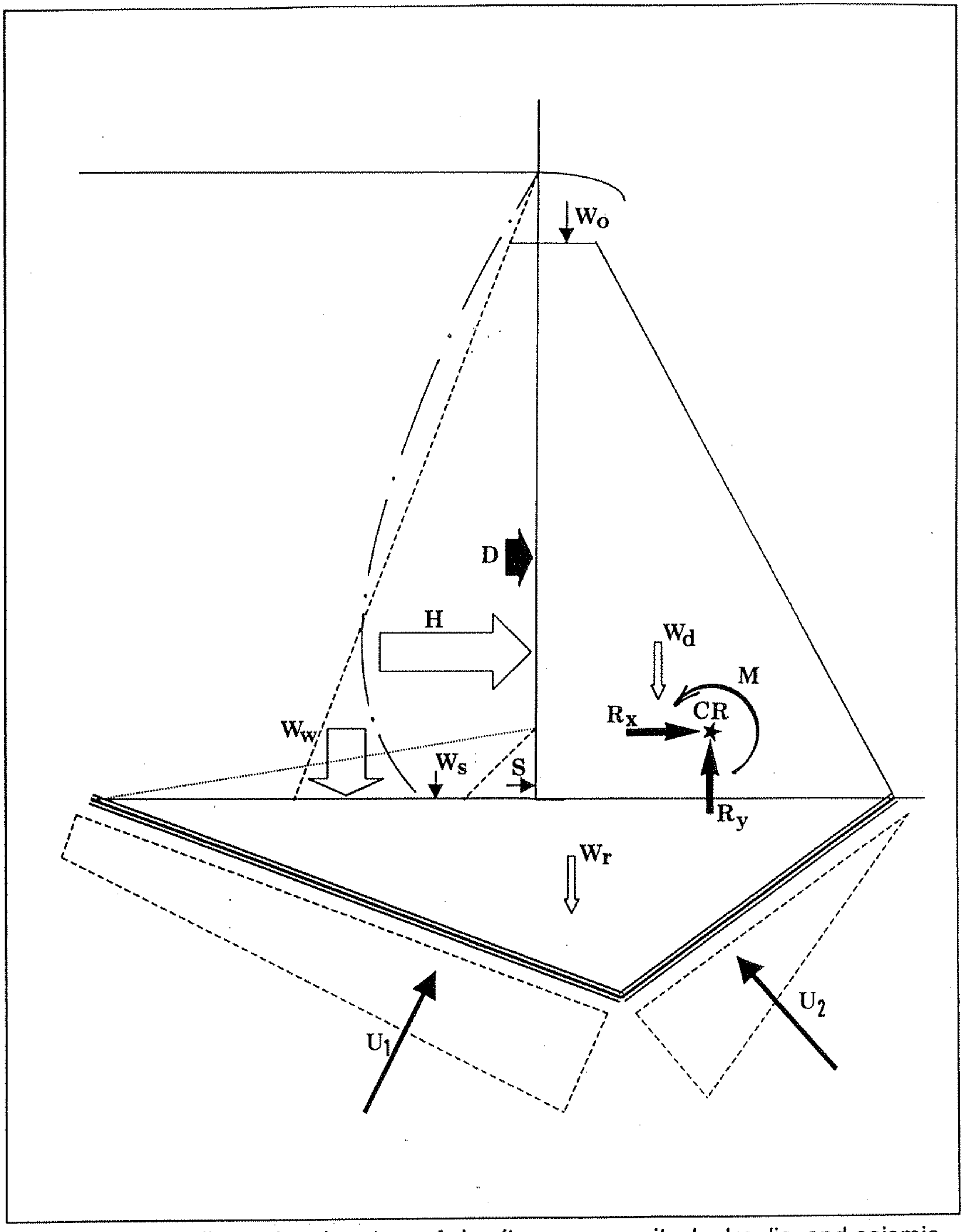

FIGURE 5. Two-dimensional system of simultaneous gravity, hydraulic, and seismic forces on dam-rock-discontinuities system

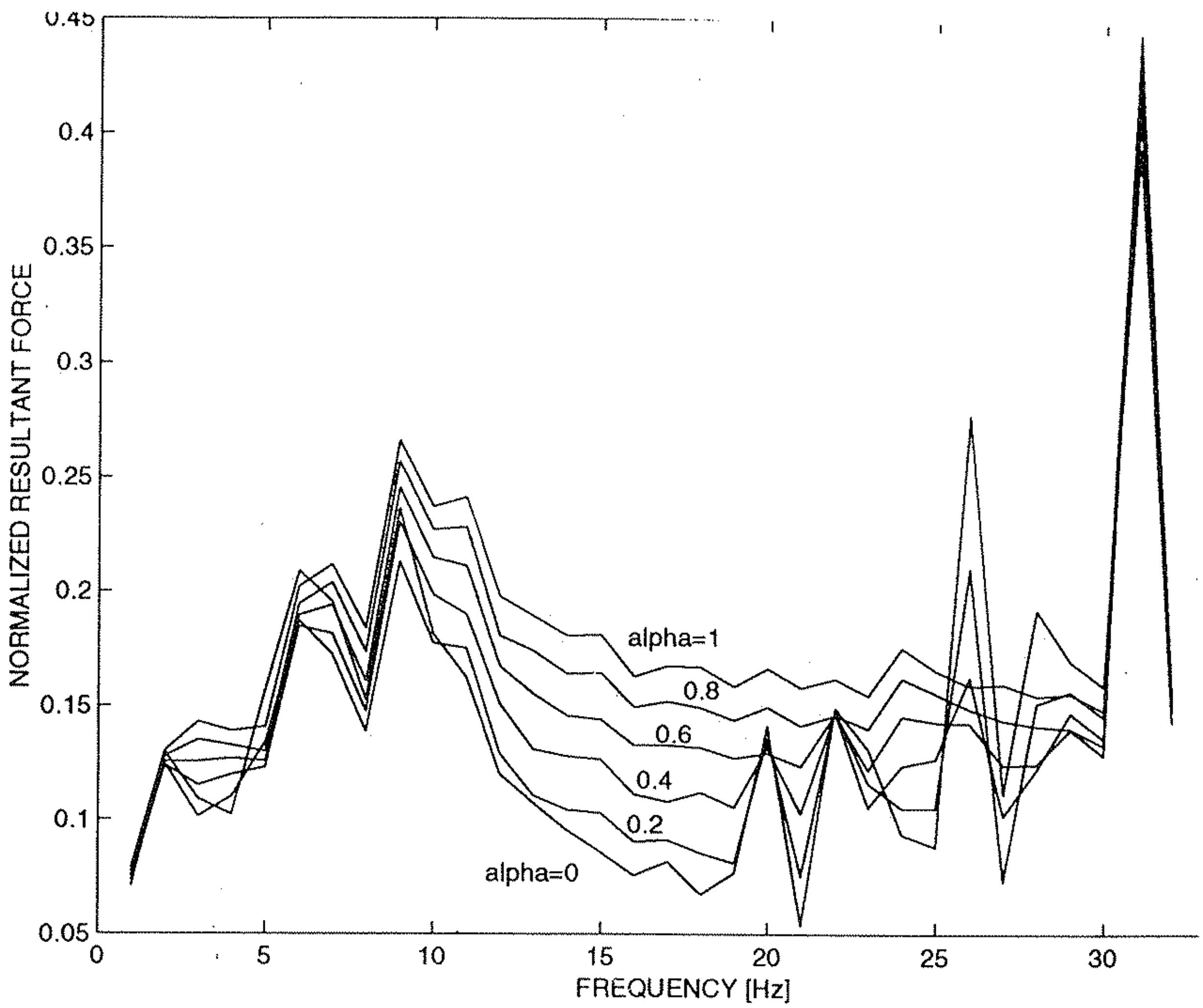

FIGURE 6. Hydrodynamic force spectrum for the San Fernando earthquake as recorded at Whittier Narrows Dam, 1971 (S53W component)

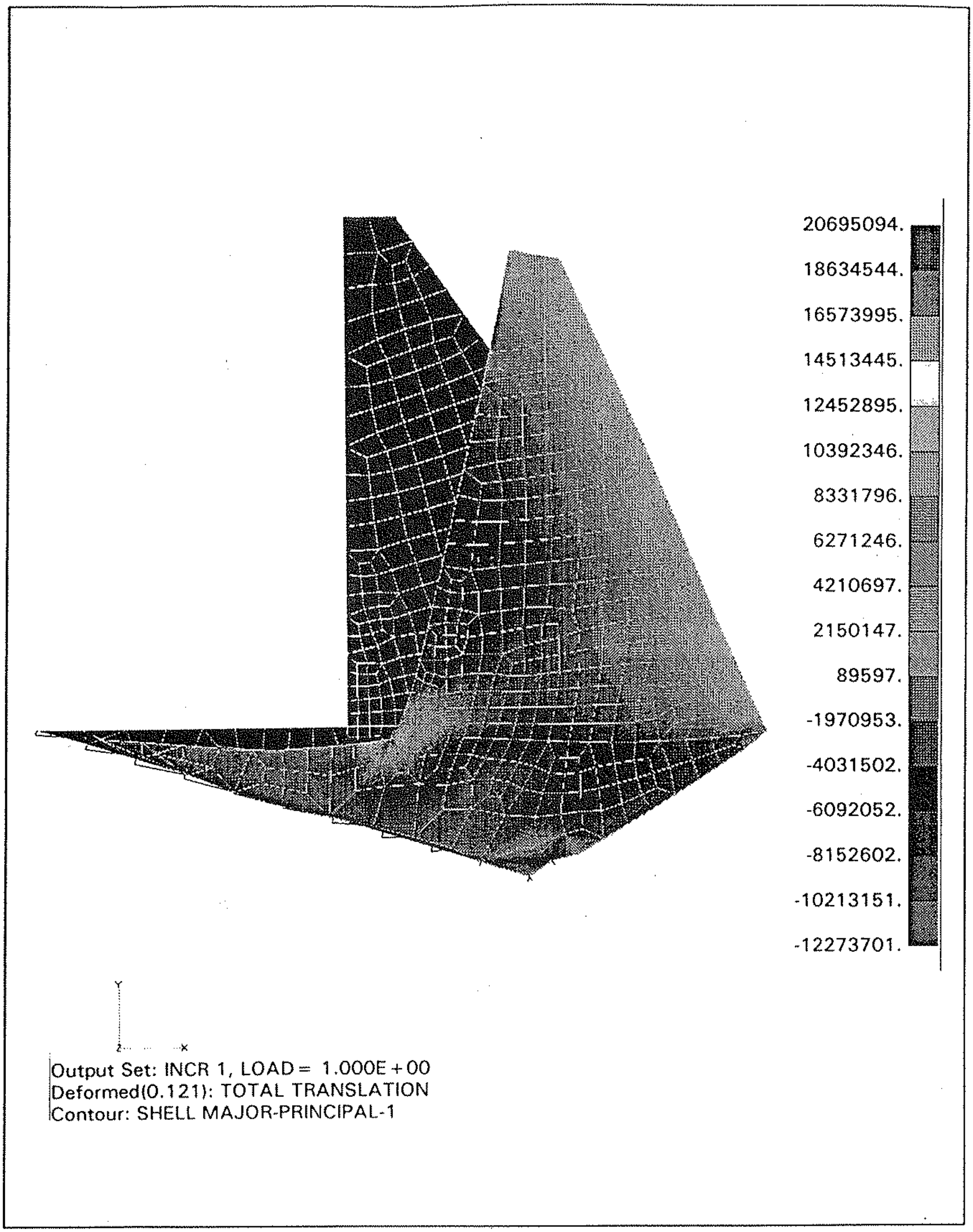

FIGURE 7. Typical 2-D dam-rock system standing on nonlinear rock joints.
Loading: Gravity + 5m overtopping + earthquake + uplift + sediments