RESEARCH NOTE

SEISMIC RESPONSE OF THE KAVAR CONCRETE FACE ROCKFILL DAM

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Abstract This study deals with the dynamic behavior of the kavar concrete face rockfill dam which is the first dam of this type to be constructed in a highly active seismic prone area, situated in the state of Fars southern part of the Islamic Republic of Iran. The finite element method was used as a tool to carry out this study. The finite element discretization was carried out under plane strain condition by representing the body of the dam, rock system, berm on upstream and the concrete slab through an eight noded isoparametric element. To account for the interfacial behavior between concrete slab and the body of the dam, the joint element has been utilized. By using direct integration technique, analysis of the behavior of the dam for the average section was carried out. It has been found that the dam is safe with respect to design basis level (DBL) earthquake record.

Key Words Seismic Response, Dam, Rockfill, Kavar, Earthquake, Concrete, Finite Element, Fars

چکیده این تحقیق به رفتار دینامیک سد صخره‌ای جلو بتنی خاور که اولین نمونه چنین سدی است که در یک ناحیه بسیار زلزله خیز واقع در استان فارس در قسمت جنوبی کشور جمهوری اسلامی ایران ساخته می‌شود، پرداخته است. از روش المان محدود بعنوان ابزاری برای انجام تحقیق استفاده شده و المان بندی تحت کرنش تخت از طریق نمایش دادن سیستم بدنه، صخره، خاک‌ریز و بتون توسط هشت المان دارای ابعاد یکسان انجام شده است. به منظور در نظر گرفتن رفتار فصل مشترک بدنه سد با بتون، عضو اتصال دهنده مورد استفاده قرار گرفته است. از طریق انتگرال‌گیری مستقیم، رفتار سد در محل سطح مقطع متوسط بررسی شده است. معلوم شده است که مقاومت سد از نظر سطح مبنای طراحی در مقابل زلزله قابل اطمینان است.

1. INTRODUCTION

During the last two decades the concrete face rockfill dam, due to its inherent advantage over central core earth type dam, has become increasingly popular. Hence, in most cases it is the first choice of the consulting engineers.

Although several high concrete face rockfill dams have been constructed in different part of the world, the notable among them are Cathena (Wikins et al. [1]), Anchicaya (Regalado et al. [2]), Areia (Pinto et al. [3]) and Xibeikou (Sizheng et al. [4]). Only a few researchers such as Gilles [5], Sayed Khaleed et al. [6] and

Noorzaei et al. [7] have used the finite element method for analyzing the dam behavior. Also, Nasim Uddin et al. [8] and Gazetas et al. [9] presented the dynamic response of a 100 m height concrete faced rockfill dam by using the ADINA software. The beam element was used to model the slab and the interface characteristics of the slab and the body of the dam were presented using the interface element. It has been shown that even high acceleration at the crest level is not very serious for the safety of the dam. The seismic analysis of the concrete faced gravel-fill dams was presented by Roa et al. [10] without considering the stiffness of the slab, but accounting for hydrodynamic effect. They concluded that there is no significant effect of this factor on the behavior of the dam.

However, little literature is available on such types of structure, particularly with regards to finite element modeling during earthquakes.

Due to the fact that the concrete facing slab plays a major role in the safety of the dam in order to prevent the seepage, so far less attention has been paid to the behavior of this important element. Most of the time it was designed as an isolated structure.

In this research, an attempt has been made to consider the concrete slab together with the body of the dam as a single compatible unit using the finite element technique. Also the interfacial behavior of the concrete slab and the body of the dam has been presented through the interface element. Finally the application of the proposed model has been demonstrated by analysing the Kavar concrete face rockfill dam which is to be constructed in the state of Fars, Islamic Republic of Iran.

2. DYNAMIC RESPONSE

The dynamic analysis of concrete face rockfill dams involves the solution of the well known dynamic equation of motion.

$$[M]\{u''\} + [C]\{u'\} + [K]\{u\} = \{f(t)\} \qquad (1)$$

where [M], [C] and [K] are the mass, damping and stiffness matrices, respectively; and u, u' and u" are the displacement, velocity and acceleration of the nodes.

In direct integration methods, the time discretization is directly performed in Equation 1, allowing it to obtain the solution for successive time steps. So, in these methods the total Earthquake record time is divided into several time steps, Δt, in which an approximation is applied to the displacements, velocities and accelerations. Basically, the solution progresses knowing the vectors u_n, $\ddot{E}_n$ and u''_n at time t_n and calculating the corresponding values at time $t_{n+1} = t_n + \Delta t$.

In dynamic analysis of such dams, the Newmark direct integration method is frequently used, because it is accurate and unconditionally stable.

The basic assumption of this method is that the accelerations vary linearly during each time increment. It assumes that:

$$\{u''\}_{t+\Delta t}=\{u'\}_t+[(1-\beta)\{u''\}_t-\beta\{u''\}_{t+\Delta t}]\Delta t \qquad (2)$$

$$\{u\}_{t+\Delta t} = \{u\}_t + \{u'\}_t\ \Delta t + [(0.5-\alpha)\{u''_t\} + \alpha\{u''\}_{t+\Delta t}]\ \Delta t^2 \qquad (3)$$

where the parameters $\propto$ and β are suitably defined in order to obtain a stable and accurate time marching. Newmark proposed $\beta = 1/2$ and $\alpha = 1/4$ for unconditional stability.

Solving Equation 3 for $\{u''\}_{t+\Delta t}$ and substituting in Equation 2, $\{u'\}_{t+\Delta t}$ and $\{u''\}_{t+\Delta t}$ are obtained as functions of $\{u\}_{t+\Delta t}$ and values at the previous time step.

Establishing the equilibrium at $t+\Delta t$, an equation of the form:

$$[M]\{u'\}_{t+\Delta t} + [C]\{u'\}_{t+\Delta t} + [K]\{u\}_{t+\Delta t} = \{f(t+\Delta t)\} \qquad (4)$$

can be derived, which can be solved for $\{u\}_{t+\Delta t}$.

This procedure is useful in earthquake analysis when accelerograms are used to characterize the ground motion, or when structural nonlinear effects are present.

3. JOINT/INTERFACE ELEMENT FORMULATION

In many problems of soil-structure interaction, modeling of rock masses and most of the problems involving relative movement, joint or interface elements are used in the finite element modeling.

The joint element has been used in this study to model the interfacial behavior of the body of the dam on upstream face and the concrete slab.

Several joint elements have been developed over the past two decades notable among which are due to Goodman et al. [11], Zienkiewicz et al. [12], Ghabaussi et al. [13], Buraghian et al. [14], Pande et al. [15], King et al. [16], Beer [17] and Viladkar et al. [18]. A brief description of the formulation of a joint element sandwitched between two eight noded isoparametric elements is presented here.

A typical parabolic curved joint element is shown in Figure 1. The pairs 1-1 , 2-2 , 3-3 are usually close to each other, but each of the elements on the top and bottom of the joint element have different material properties.

Since the element is of isoparametric type, we can write :

$$X = \Sigma N_i x_i \quad : Y = \Sigma N_i\, y_i \qquad (5)$$
$$U = \Sigma N_i u_i \quad : V = \Sigma N_i\, v_i$$
$$(i = A,B,C)$$

The shape function of the node A,B and C can be written as:

$$NA = -\xi\ (1-\xi)/2,\ NB = (1-\xi^2),\ NC = \xi\ (1+\xi)/2 \qquad (6)$$

The relative displacements can be expressed as

$$\{\Delta\} = \{\Delta U_A, \Delta V_A, \Delta U_B, \Delta V_B, \Delta U_C, \Delta V_C\}^T \qquad (7a)$$

$$= \{u^t{}_1 - u^b{}_1, v^t{}_1 - v^b{}_1, u^t{}_2 - u^b{}_2, v^t{}_2 - v^b{}_2, u^t{}_3 - u^b{}_3, v^t{}_3 - v^b{}_3\}^T$$

Where the notation t and b correspond to the top and bottom element of the continuum in matrix notation $\{\Delta\}$ which can be expressed as :

$$\begin{bmatrix} \Delta U_A \\ \Delta V_A \\ \Delta U_B \\ \Delta V_B \\ \Delta U_C \\ \Delta V_C \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} u_1{}^t \\ v_1{}^t \\ u_2{}^t \\ v_2{}^t \\ u_3{}^t \\ v_3{}^t \\ u_1{}^b \\ v_1{}^b \\ u_2{}^b \\ v_2{}^b \\ u_3{}^b \end{bmatrix} \qquad (7b)$$

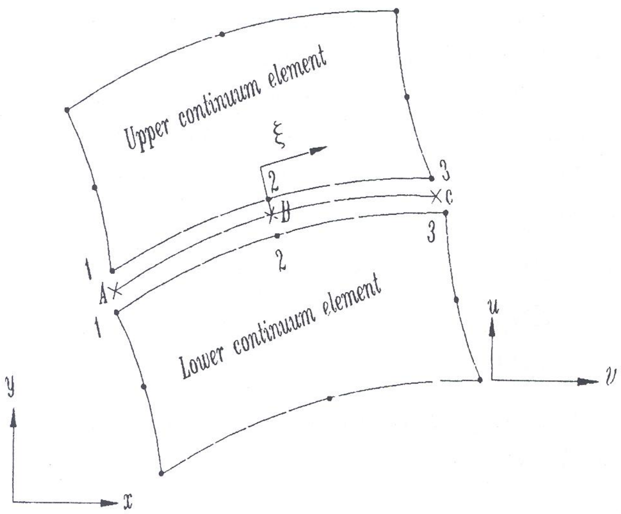


Figure 1. Interface element with two adjacent continuum elements.

The above expression can be presented in a simple form as

$$\underset{6*1}{\{\Delta\}} = \underset{6*12}{[T]} \underset{12*1}{\{\delta\}} \tag{8}$$

Strain-Displacement Relation The strain vector, $\{\xi\}$ (in this case the relative displacement) in global co-ordinates x and y at any point of the element can be expressed in terms of nodal values of relative displacements as:

$$\{\xi\}=1/t \begin{bmatrix} \Delta u \\ \Delta v \end{bmatrix} = \begin{bmatrix} NA & 0 & NB & 0 & NC & 0 \\ 0 & NA & 0 & NB & 0 & NC \end{bmatrix} \{\Delta\} \tag{9}$$

$$= [N]\,[T]\,\{\delta\}$$
$$= [B]_j\,\{\delta\}$$

$[B]_j$ = Joint element strain-displacement relationship

t = thickness of the element.

The Stress-Strain Relationship The normal stress, and the tangential stress are related to the corresponding strains as :

$$\{\sigma\} = [D]\,\{\xi\} \tag{10a}$$

$$[D] = \begin{bmatrix} kss & 0 \\ 0 & knn \end{bmatrix} \tag{10b}$$

Where kss and Knn are the normal and tangential stiffnesses respectively.

The stiffness matrix of the element can be written as :

$$[K]e = \int [B]^T_J\,[D]\,[B]_J\,dv \tag{11}$$

The global stiffness matrix is written in the usual way as :

$$[k]_g = [R]^T\,[k]^e\,[R] \tag{12}$$

$$[R] = \begin{bmatrix} \frac{1}{S}\frac{dx}{d\xi} & \frac{1}{S}\frac{dy}{d\xi} \\ -\frac{1}{S}\frac{dy}{d\xi} & \frac{1}{S}\frac{dx}{d\xi} \end{bmatrix} \quad \text{and} \tag{13a}$$

$$S = [(\frac{dx}{d\xi})^2 + (\frac{dy}{d\xi})^2]^{0.5} \tag{13b}$$

4. PROGRAMMING ASPECT

The existing two dimensional finite element code for the dynamic analysis presented by Owen and Hinton [19] has been extensively modified in view of the inclusion of varieties of the elements.

The flow chart of the program is shown in Figure 2. The inclusion of the joint elements is based on the above formulation and their stiffness matrix are compared with the explicit form of the stiffness matrix presented in Appendix I.

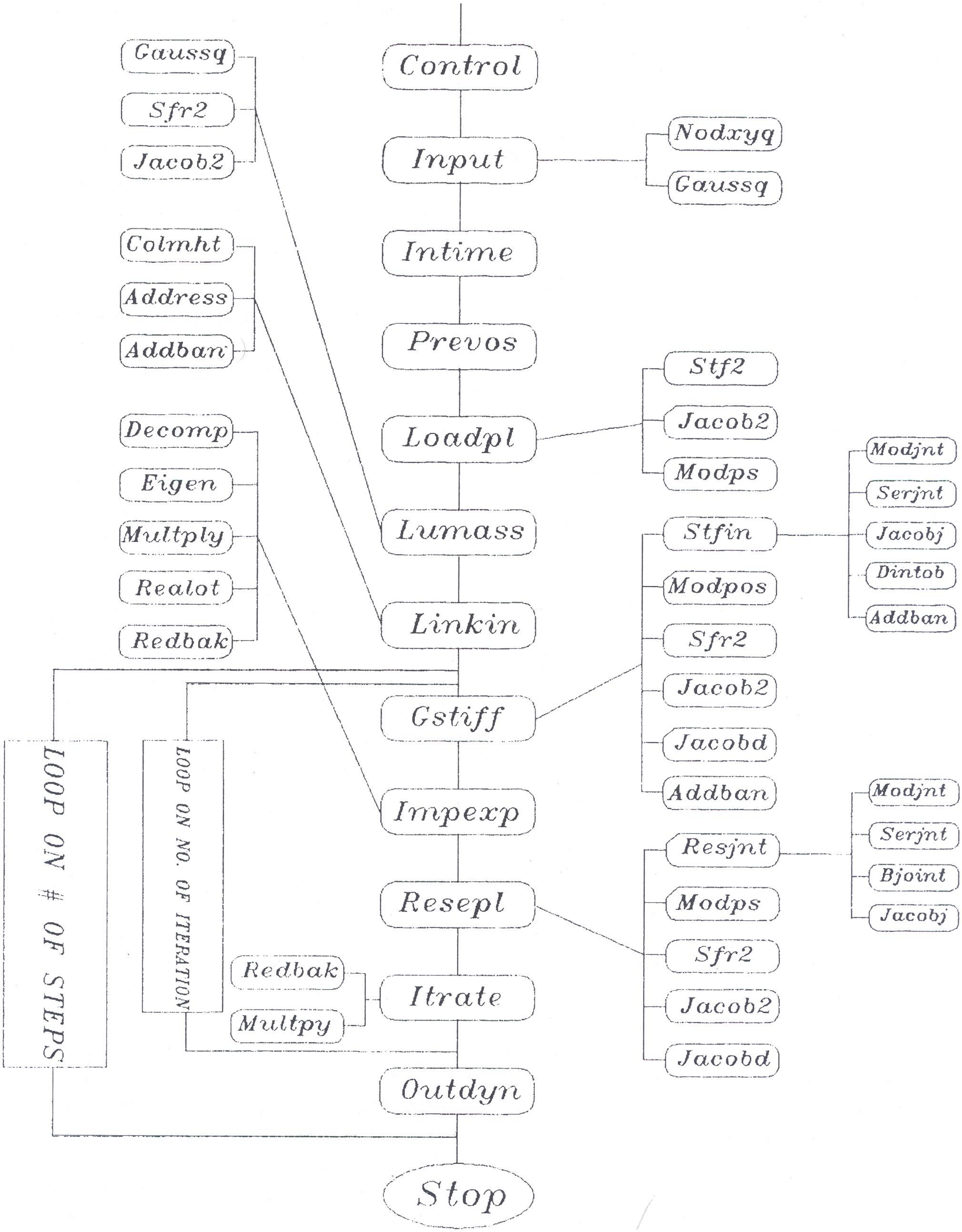


Figure 2. Flow chart of the finite element code.

5. PROBLEM DEFINITION

The plan of the Kavar concrete face dam is presented in Figure 3. Figure 4 shows the cross section of the dam along with other details. The finite element discretization of the dam section has been illustrated in Figure 5. The various elements which have been employed to show the body of the dam, rockbed, berm, boundary condition and the concrete slab are also shown in the finite element mesh. Based on the geotechnical investigation of the dam section, the material properties are selected [Kavar technical report] and presented in Figure 5.

In this investigation depending on the value of modulus of elasticity of concrete slab and body of the dam, the value of knn = 10^4 t/m is selected (Zienkiewicz et al. [12], Noorzaei [21] and Viladkar et al. [21]. Also for the condition of no bond case to avoid ill-conditioning a small value of kss = 150 t/m is selected.

The dynamic response of dam section was carried out under plane strain condition for DBL earthquake record with PG A = 0.25g .

In this study the Rayleigh damping scheme was used to obtain damping matrix; that is:

$$[c] = a\,[k] + b\,[M] \qquad (14)$$

a and b are damping parameters which are evaluated based on the following expression:

$$a = \zeta w \quad b = \frac{\zeta}{w} \qquad (15)$$

ζ = damping ratio w = circular frequency

$$w = \frac{2\pi}{T} \qquad T = 2.61\,\frac{H}{V_s} \qquad (16)$$

The expression for velocity is presented (Daghigh [22]) as:

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \qquad (17)$$

T = Natural period of vibration
H = Height of the dam
E = Modulus of elasticity
υ = Poisson ratio
f = density
V_s = shear wave velocity

Using Equations 15 to 17 for the value of ζ = 3% , 5% , 8% and 10% an averaged value of a and b has been selected.

6. RESULTS AND DISCUSSION

By using the direct Newmark intergration technique, the record of the earthquake is divided into six hundred steps with damping parameters as a = 1.0638 and b = 0.00397.

To study the variation of displacement in the dam body three nodal points corresponding to crest, berm and ground level have been selected and their variations are presented in Figure 7 with maximum total displacement of 10 cm at the crest level

The contours of maximum and minimum principal stresses (t/m^2) are plotted in Figures 8 and 9. From these figures, it can be noted that the areas of over stress exist in the zone of upstream face of the dam body and the concrete slab. It is due to the fact that there is significant differences in the stiffeness of the adjacent materials. Also, It can be seen from these figures that stress variation within the dam body and foundation are within their permissible limit.

The plot of acceleration versus time at midcrest of the dam is shown in Figure 10 with maximum acceleration of 1.7g.

As far as the behavior of the concrete slab is concernd, unfortunately so far little literature is available regarding the behavior of this key element during the earthquake motion. Therefore, in the present study special attention has been paid to this important element. So, the slab was modeled as part of the dam with low value of shear stiffenss. Figure 11 shows the

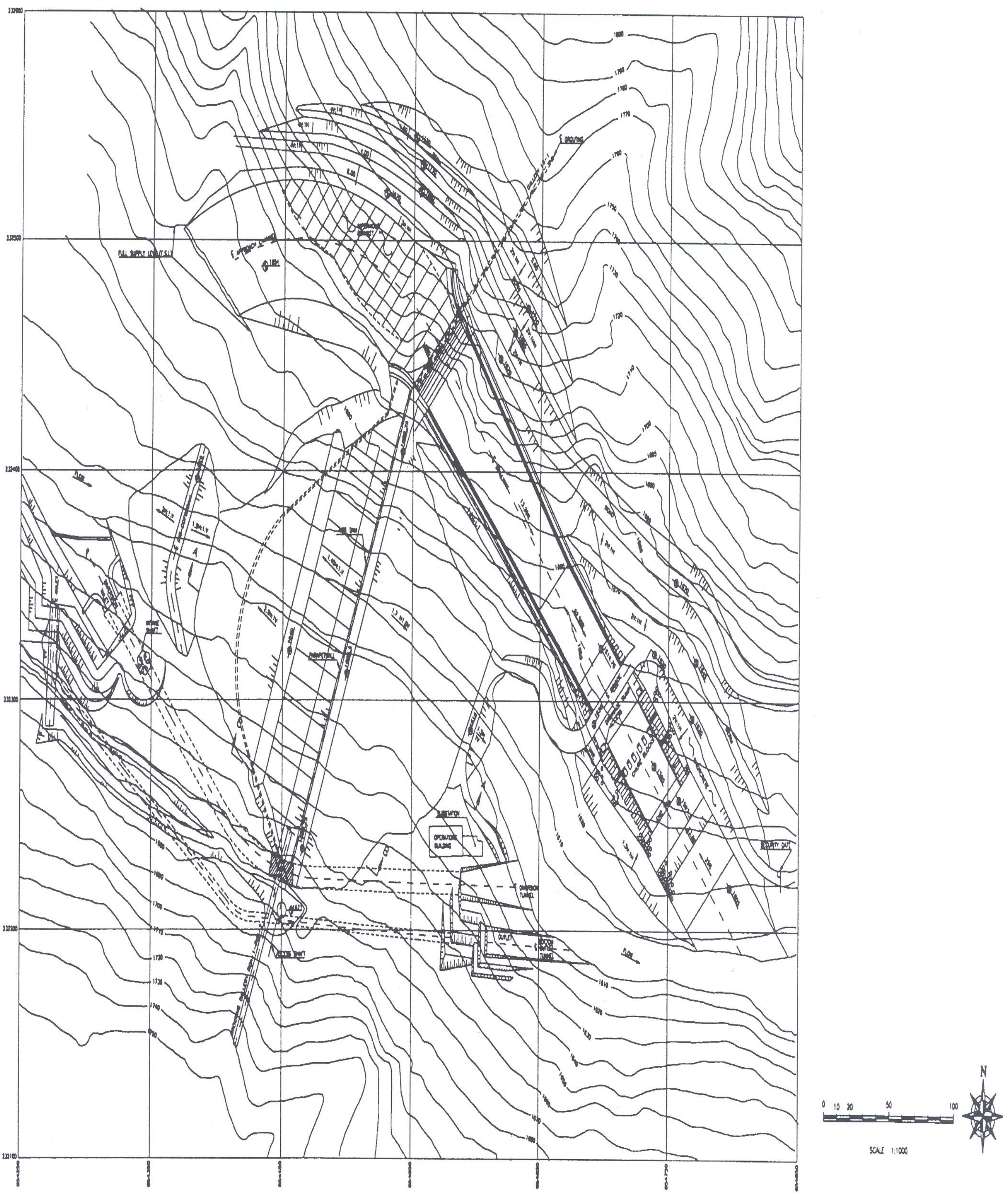


Figure 3. Plan of the Kavar dam.

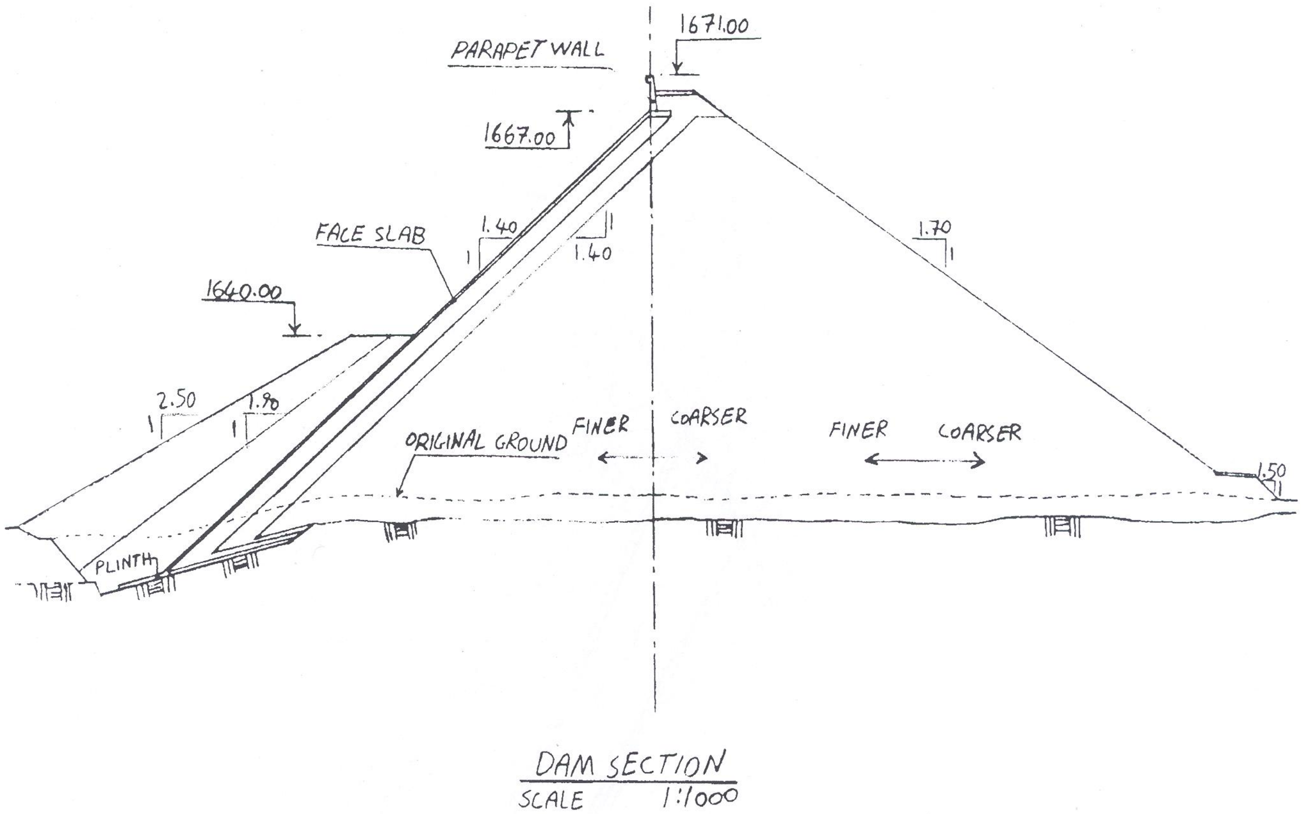


Figure 4. Dam section.

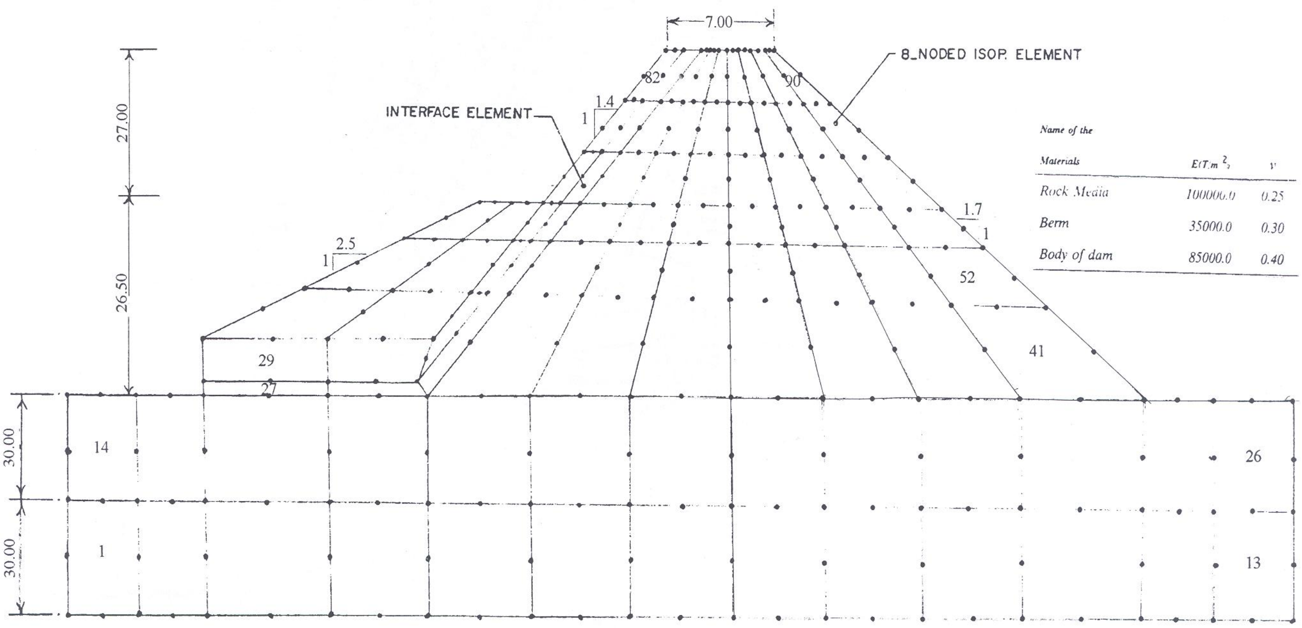


Figure 5. Finite element modeling of the Kavar dam section.

horizontal displacement of the two nodal point having same co-ordinates but one is situated at the top of the dam body at upstream face and the other on the concrete slab (same elevation).

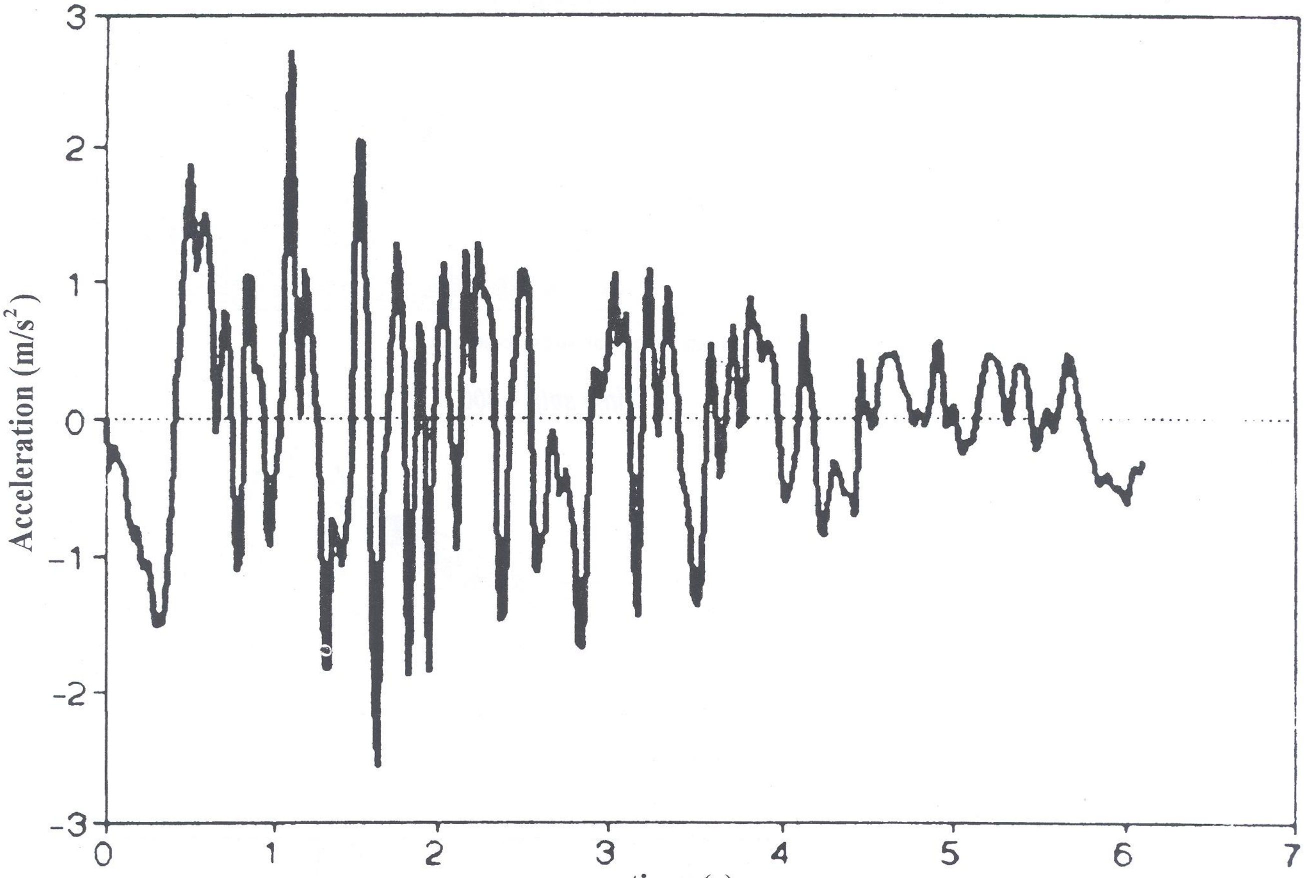


Figure 6. Horizontal earthquake records.

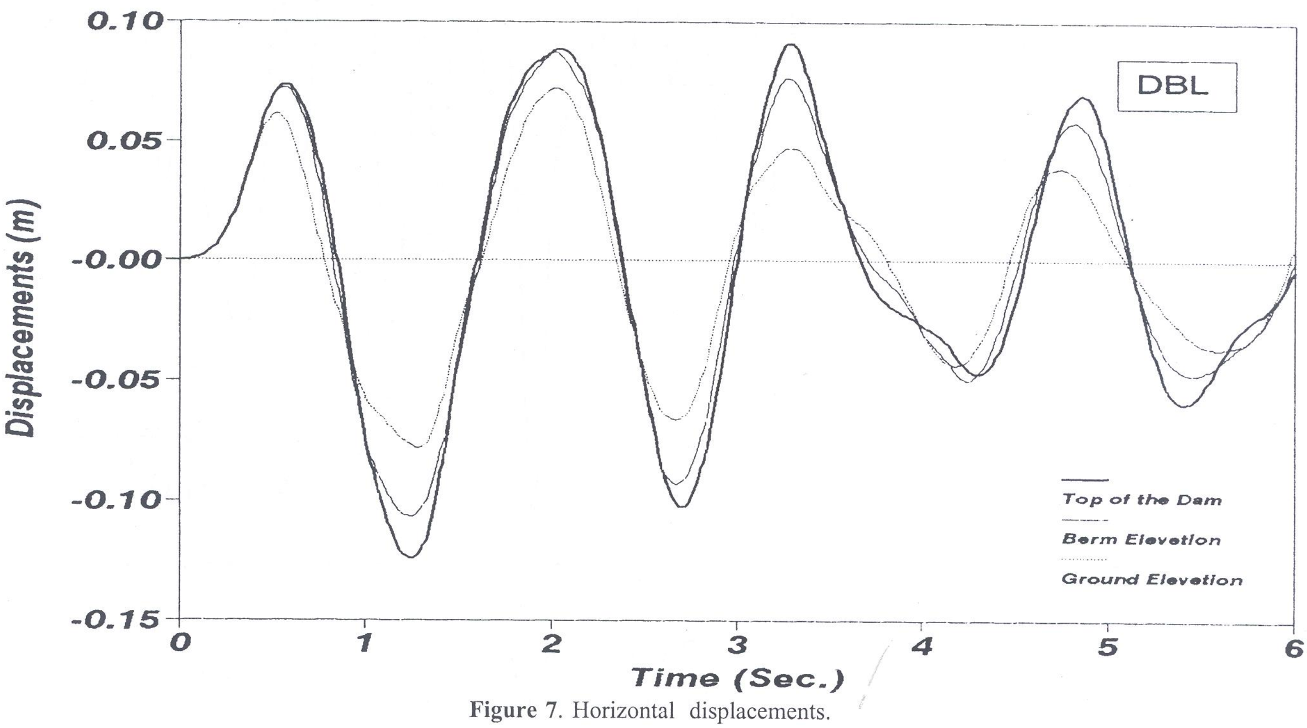


Figure 7. Horizontal displacements.

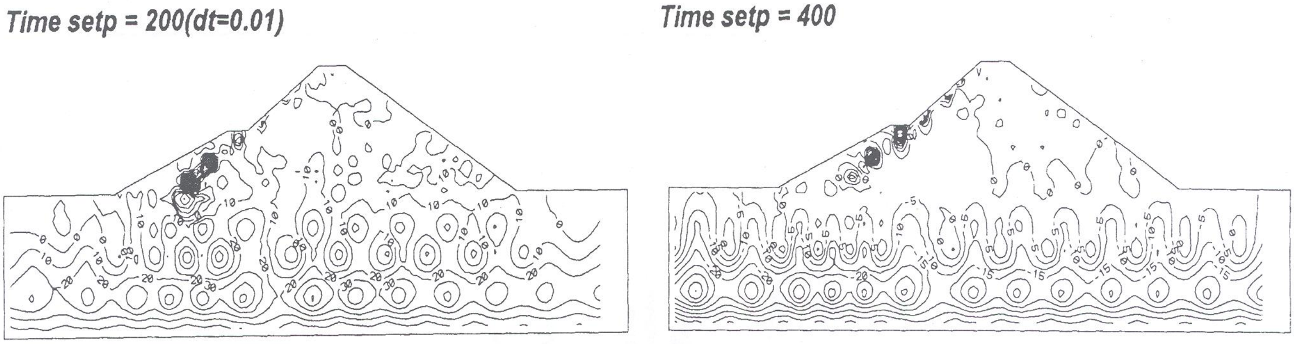


Figure 8. Maximum principal stress contours.

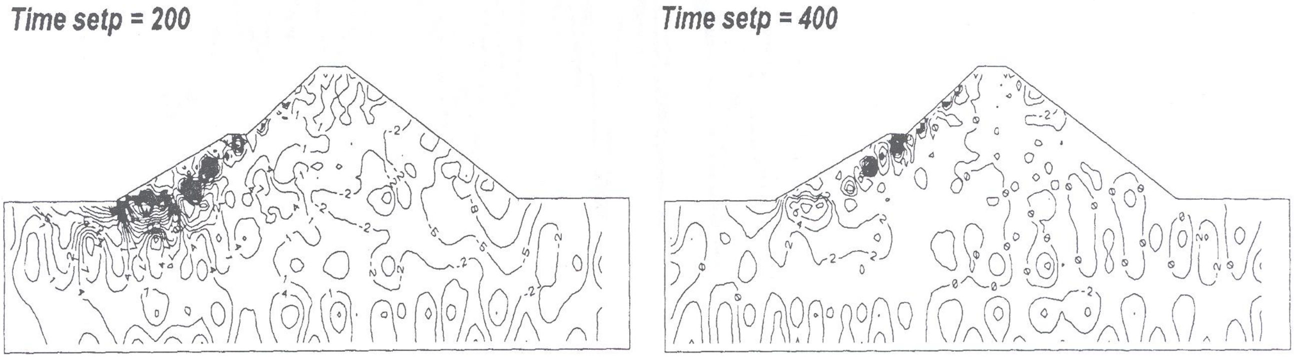


Figure 9. Minimum principal stress contours.

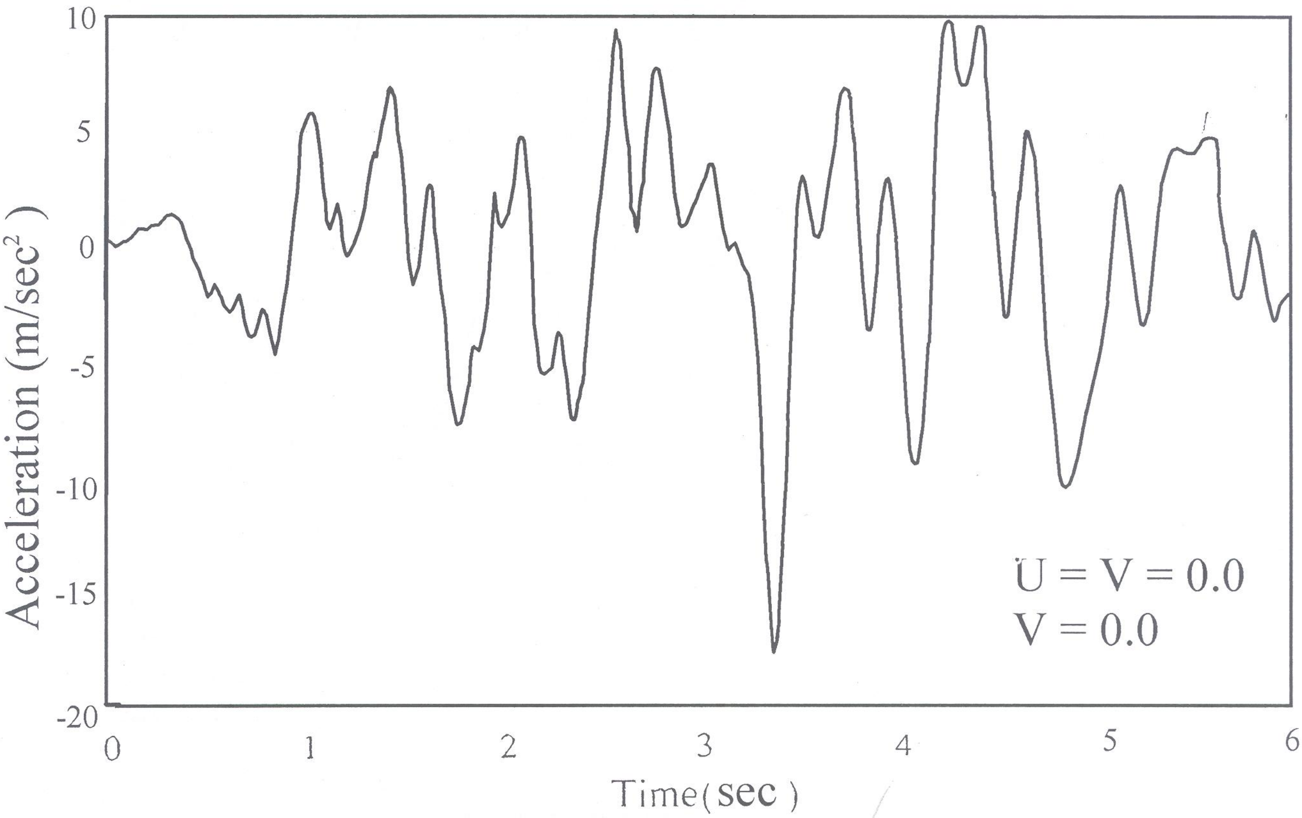


Figure 10. Horizontal acceleration at crest level.

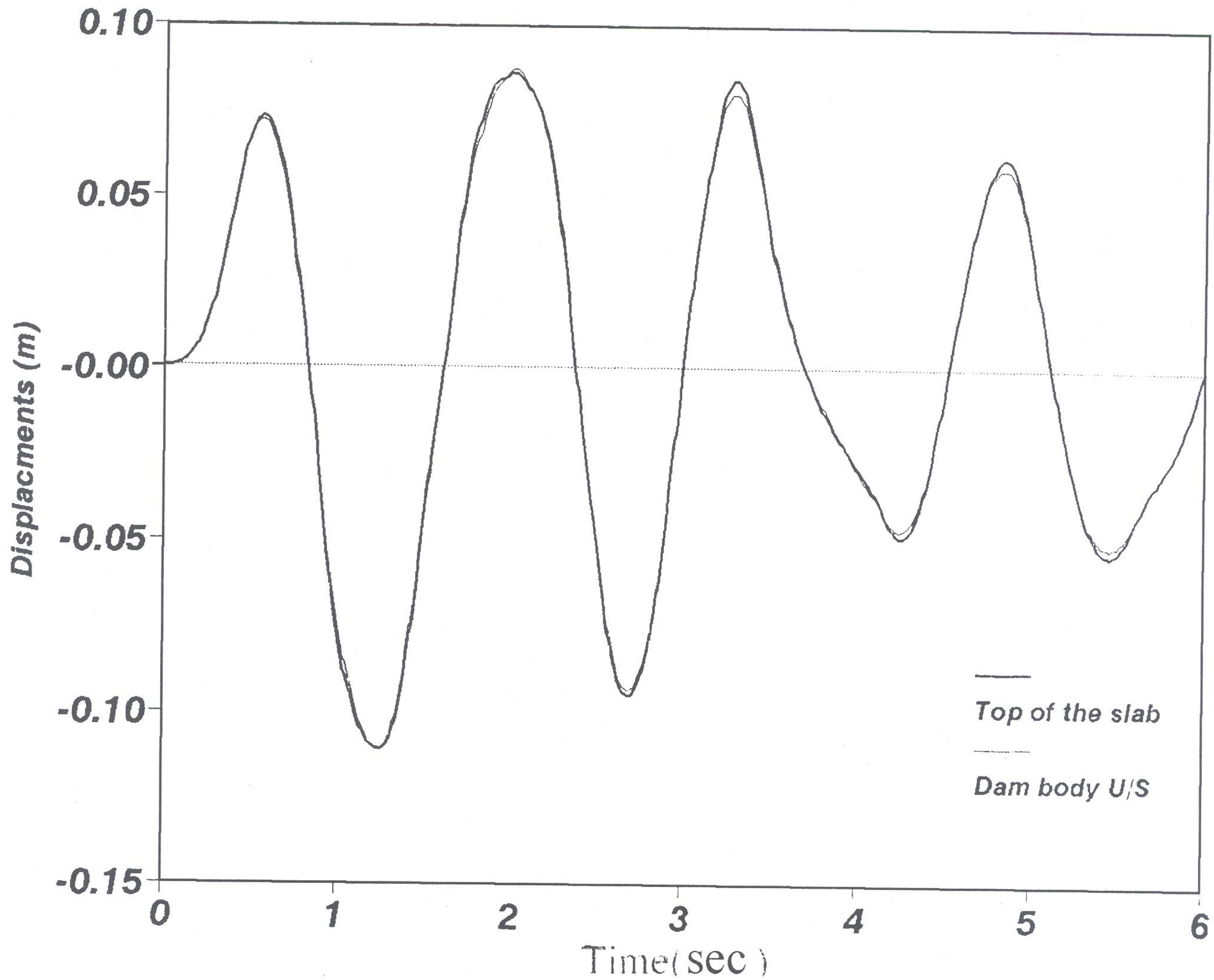


Figure 11. Horizontal displacement at crest elevation (top of dam and top of slab).

It is clear from this plot that both nodal points have similar behavior.

To study the variation of the principal stresses in the concrete slab, two Gaussian points are selected along the concrete slab, one of the points is situated at the berm level and the other is nearly at the crest elevation. Figures 12a and 12b show variation of the principal stresses (01,03) for earthquake record.

It is obvious that the dam is safe for DBL case and there is no development of the significant tensile stress in the slab. However, two layers of reinforcement with 36 millimeters diameter are suggested to be provided in both directions at 20 centimeters center to center.

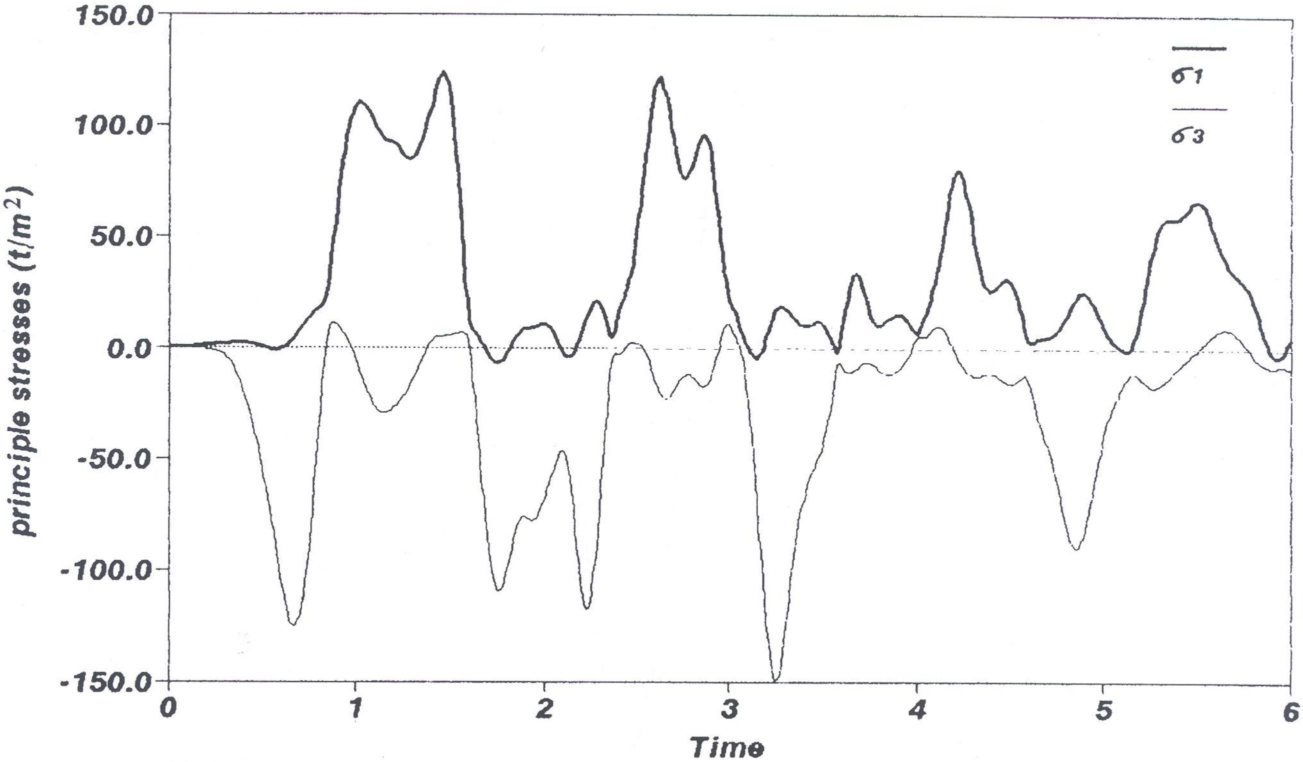
6. CONCLUSIONS

(i) - It is essential that for a realistic analysis of the concrete faced rockfill dam, the concrete face, body of the dam section and the bedding system should be considered as a single unit while carrying out the finite element idealization.

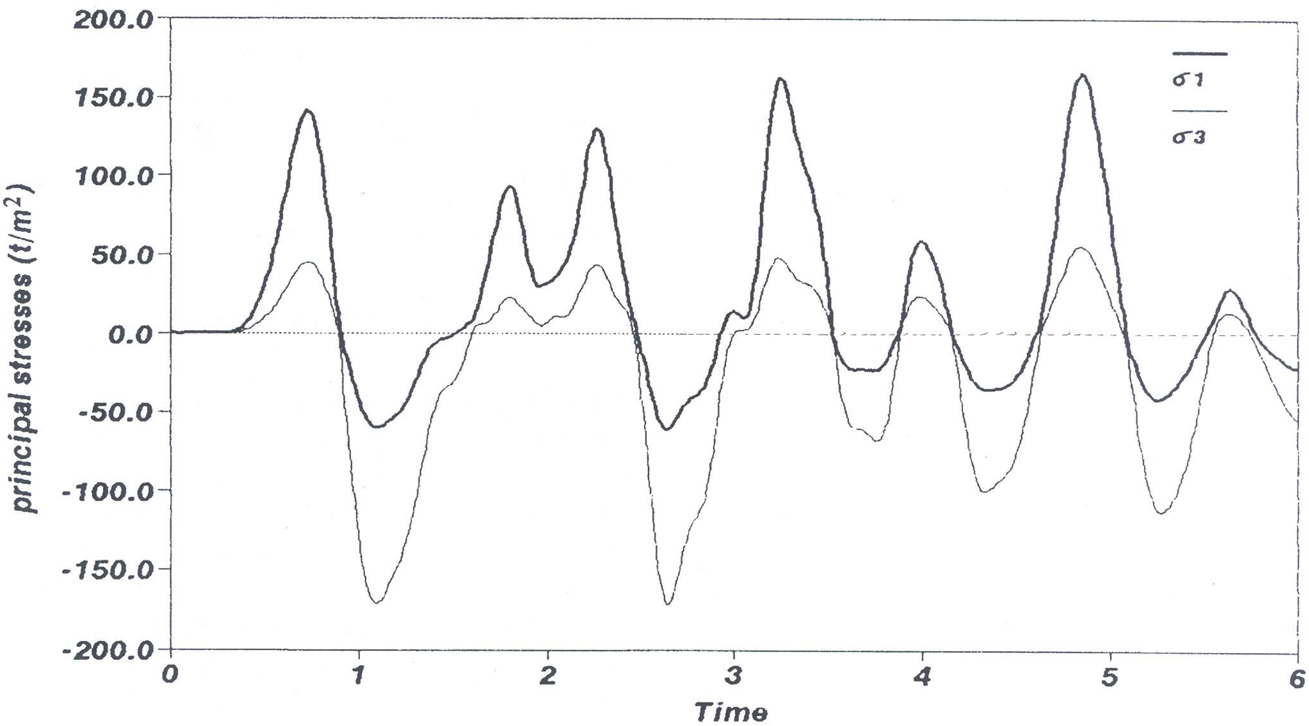
(ii) - The software developed in this course of study is multi-element in nature and can be applied for any two-dimensional problem.

(iii) - Based on this study, the dam is quite safe for the earthquake record of the design basis level.

(iv) - There is no sign of separation between the



(a)



(b)

Figure 12. Variation of principal stresses (t/m^2): (a) top of the berm level and (b) crest level.

concrete slab and body of the dam on upstream face.

APPENDIX

Stiffness Matrix of the interface Element in explicit form [k] =

$$
\begin{bmatrix}
\frac{2L}{15}K_{ss} & 0 & \frac{L}{15}K_{ss} & 0 & \frac{L}{-30}K_{ss} & 0 & \frac{-2L}{15}K_{ss} & 0 & \frac{-L}{15}K_{ss} & 0 & \frac{L}{30}K_{ss} & 0 \\
 & \frac{2L}{15}K_{nn} & 0 & \frac{L}{15}K_{nn} & 0 & \frac{-L}{30}K_{nn} & 0 & \frac{-2L}{15}K_{nn} & 0 & \frac{-L}{15}K_{nn} & 0 & \frac{L}{30}K_{nn} \\
 & & \frac{8L}{15}K_{ss} & 0 & \frac{L}{15}K_{ss} & 0 & \frac{-L}{15}K_{ss} & 0 & \frac{-8L}{15}K_{ss} & 0 & \frac{-L}{15}K_{ss} & 0 \\
 & & & \frac{8L}{15}K_{nn} & 0 & \frac{L}{15}K_{nn} & 0 & \frac{-L}{15}K_{nn} & 0 & \frac{-8L}{15}K_{nn} & 0 & \frac{-L}{15}K_{nn} \\
 & & & & \frac{2L}{15}K_{ss} & 0 & \frac{L}{30}K_{ss} & 0 & \frac{-L}{15}K_{ss} & 0 & \frac{-2L}{15}K_{ss} & 0 \\
 & & & & & \frac{2L}{15}K_{nn} & 0 & \frac{L}{15}K_{nn} & 0 & \frac{-L}{15}K_{nn} & 0 & \frac{-2L}{15}K_{nn} \\
 & & & & & & \frac{2L}{15}K_{ss} & 0 & \frac{L}{15}K_{ss} & 0 & \frac{-L}{30}K_{ss} & 0 \\
 & & \text{symmetric} & & & & & \frac{2L}{15}K_{nn} & 0 & \frac{L}{15}K_{nn} & 0 & \frac{-L}{30}K_{nn} \\
 & & & & & & & & \frac{8L}{15}K_{ss} & 0 & \frac{L}{15}K_{ss} & 0 \\
 & & & & & & & & & \frac{8L}{15}K_{nn} & 0 & \frac{L}{15}K_{nn} \\
 & & & & & & & & & & \frac{2L}{15}K_{ss} & 0 \\
 & & & & & & & & & & & \frac{2L}{15}K_{nn}
\end{bmatrix}
$$

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