EFFECT OF FOUNDATION FLEXIBILITY ON DAM-RESERVOIR-FOUNDATION INTERACTION

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ABSTRACT

Investigation of the behavior of dams against seismic loads is a key factor for dam safety requirements. One of the most important problems in evaluation of seismic behavior of concrete gravity dams is dam-reservoir-foundation interaction. Hydrodynamic pressures generated due to seismic forces and Fluid-Structure-Soil Interaction (FSS); are inevitable. In this paper, the basic equation involved the water-structure-foundation interaction and the effective factors are considered for concrete gravity dams. Dam-reservoir-foundation interaction has been investigated utilizing seismic analysis. 2-D dam-reservoir-foundation coupled system is analyzed using FEM via ANSYS code. Dam and foundation are assumed to be linear and elastic while reservoir water is considered acoustic, inviscid and incompressible. The dam and foundation have been idealized by considering linear, elastic and plane stress conditions. The modeling of reservoir has been carried out by fluid acoustic element and proper consideration of fluid boundary and initial conditions. The effect of foundation flexibility has been obtained by considering various dam-foundation rock interaction ratios i.e. modulus of elasticity of foundation to modulus of elasticity of dam. Results show that both foundation mass and flexibility have an outstanding impact on the behavior of dams and is necessary to consider their impact while simulating seismic response of concrete gravity dams.

Keywords: Seismic Response; Concrete Gravity Dams; Foundation Flexibility; Dam- Reservoir-Foundation Interaction, ANSYS.

1 INTRODUCTION

During the recent years, the seismic behavior of concrete gravity dams was in the center of consideration of dam engineers. Numerous researches have been conducted in order to determine how the dams behave against the seismic loads. Many achievements were obtained in the process of analysis and design of concrete dams. In this paper, we study the dam-reservoir-foundation interaction during an earthquake. For this purpose, a two-dimensional finite element model of a concrete gravity dam including the dam body, a part of its foundation and a part of the reservoir was made. In addition, the proper boundary conditions were used in both reservoir and foundation in order to absorb the energy of waves at the far end boundaries. Using the finite element method seismic analysis is performed to assess the impact of the foundation mass and flexibility on the seismic behavior of the dam.

2 STATE OF ART

The methods used for the analysis of concrete dams under earthquake loading range from the simple pseudo-static method initially proposed by Westergaard (1933) to advanced numerical methods that include the well-known FEM. Westergaard [1] introduced an approach to determine approximately the linear response of the dam-reservoir system by a number of masses that are added to the dam body. The method proposed by Westergaard assumes that the hydrodynamic effect on a rigid dam is equivalent to the inertial force resulting from a mass distribution added on the dam body. The dam-reservoir system can be categorized as a coupled field system in a way that these two physical domains interact only at their interface [2]. To simplify and economize the finite element modeling of an infinite reservoir, the far-end boundary of the reservoir has to be truncated. Sommerfeld boundary condition [3] is an appropriate boundary condition for the truncated part of the reservoir. Hydrodynamic pressure in seismic response of dam-reservoir interaction in time domain has been investigated [4]-[6]**.** Preliminary design and evaluation of concrete gravity sections is usually performed using the simplified response spectrum method proposed by Fenves and Chopra [7]. A standard fundamental mode of vibration, representative of typical sections, is used in this method. This mode shape does not take into account the foundation flexibility since it is representative of a standard concrete gravity section on rigid foundation. As an alternative, the first mode of vibration of the concrete section could be estimated using a finite element model with massless foundation. Fenves and Chopra [8] studied the dam-reservoir-foundation rock interaction in a frequency domain linear analysis. In the work presented by Gaun et. al [9], an efficient numerical procedure has been described to study the dynamic response of a reservoir-dam-foundation system directly in the time domain. Ghaemian et. al [10] showed that the effects of foundation's shape and mass on the linear response of arch dams are considerable. The dam–foundation interaction effects are typically presented by a "standard" mass-less foundation model [11]. In this case, it is assumed that the displacement at the bottom of the foundation vanishes and roller supports is placed at the vertical sides of the foundation. The most widely used model for soil radiation damping is the one of Lysmer and Kuhlemeyer [12]. In this model the foundation is wrapped by dashpots tuned to absorb the S and P waves. In this model, modeling the radiation damping on the far–end boundary of the massed foundation, 2- node elements as boundary elements are used to apply the lumped dashpot on the far–end nodes of the massed foundation model. The viscous boundary condition is applied on the far–end boundary of the foundation to prevent the wave reflection form the artificial boundary of the infinite media in finite element analysis. The most common soil–structure interaction (SSI) approach is based on the "added motion" formulation. This formulation is valid for free–field motions caused by earthquake waves generated from all sources. The method requires that the free–field motions at the base of the structure be calculated prior to the soil–structure interaction analysis [13].

3 PROBLEM STATEMENT

For the structure on the rigid foundation, the input seismic acceleration gives rise to an overturning moment and transverse base shear. As the rock is very stiff, these two stress resultants will not lead to any (additional) deformation or rocking motion at the base. For the structure founded on flexible soil, the motion of the base of the structure will be different from the free-field motion because of the coupling of the structure-soil system. This process, in which the response of the soil influences the motion of the structure and response of the structure influences the motion of the soil, is referred to as soil-structure interaction (SSI) presented by Wolf (1985) [14]. The objective of this paper is to assess the impact of foundation flexibility and dam-reservoir-foundation interaction on seismic response of high concrete gravity dams. A two-dimensional (2D) finite-element (FE) model is used to investigate the effects of foundation flexibility and dam-reservoir-foundation interaction on the seismic response of a typical non-overflow concrete gravity dam section with full reservoir. The dam height is 110 meters, the downstream slope is 0.9:1, and the upstream face is assumed vertical. The crest of the dam is 10 m wide, and a rectangular section is assumed for the top 10 m of the monolith. Standard material properties are assumed, with unit density of concrete = 2400 kg/m^3, and modulus of elasticity *Es= 24 GP*. Radiation damping in the foundation is not considered in the current study. In this study, a dam-reservoir-foundation system is analyzed linearly using ANSYS code. The dam-reservoir interaction is solved by a coupled solution procedure while Sommerfeld boundary condition is applied at the reservoir's far-end truncated boundary. The foundation is defined as a different part from the structure with different modulus of elasticity. In the present study, a time domain seismic analysis of the problem is developed by coupling the finite element method for the infinite reservoir, infinite foundation and finite dam domain. An efficient coupling procedure is formulated by using the coupling coincide nodes method. The effect of foundation flexibility has been obtained by considering various dam-foundation rock interaction ratios E_f/E_c i.e. modulus of elasticity of foundation E_f to modulus of elasticity of dam concrete E_c. Figure 1 shows the problem idealization.

4 COUPLED FLUID- STRUCTURE-FOUNDATION FORMULATION

Applying the standard Galerkin's method to simulate of dam-reservoir-foundation interaction is performed. The discretized structural dynamic equation including the dam and foundation rock subjected to ground motion can be formulated using the finite-element approach as [15]:

$$\boldsymbol{M_s \ddot{u}_e + C_s \dot{u}_e + K_s u_e = -M_s \ddot{u}_g + Q\, P_e} \tag{1}$$

Where $\boldsymbol{M_s}$, $\boldsymbol{C_s}$ and $\boldsymbol{K_s}$ are the structural mass, damping and stiffness matrices, respectively, $\boldsymbol{u_e}$ is the nodal displacement vector with respect to ground and the term $\boldsymbol{QP_e}$ represents the nodal force vector associated with the hydrodynamic pressure produced by the reservoir. In addition, $\ddot{u}e$ and $\ddot{u}g$ are the relative nodal acceleration and nodal ground acceleration vectors, respectively. The term Q is referred to as the coupling matrix. The discretization of hydrodynamic pressure equation to get the matrix form of the wave equation as [15]:

$$\boldsymbol{M_f \ddot{P}_e + C_f \dot{P}_e + K_f\, P_e + \rho_w\, Q^T(\ddot{u}_e + \ddot{u}_g) = 0} \tag{2}$$

Where $\boldsymbol{M_f}$, $\boldsymbol{C_f}$ and $\boldsymbol{K_f}$ are the fluid mass, damping and stiffness matrices, respectively and $\boldsymbol{P_e}$; $\boldsymbol{\ddot{u}_e}$ and $\boldsymbol{\ddot{u}_g}$ are the nodal pressure, relative nodal acceleration and nodal ground acceleration vectors, respectively. The term $\boldsymbol{\rho_w\, Q^T}$is also referred to as the transpose of the coupling matrix. The dot represents the time derivative. Equations (1) and (2) describe the complete finite-element discretized equations for the dam-water-foundation rock interaction problem and can be written in an assembled form as [15]-[17]:

$$\begin{bmatrix} \boldsymbol{M_s} & \boldsymbol{0} \\ \boldsymbol{M_{fs}} & \boldsymbol{M_f} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\ddot{u}_e} \\ \boldsymbol{\ddot{P}_e} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C_s} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{C_f} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\dot{u}_e} \\ \boldsymbol{\dot{P}_e} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K_s} & \boldsymbol{K_{fs}} \\ \boldsymbol{0} & \boldsymbol{K_f} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u_e} \\ \boldsymbol{P_e} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{-M_s \ddot{u}_g} \\ \boldsymbol{-M_{fs} \ddot{u}_g} \end{Bmatrix} \tag{3}$$

Where $\mathbf{K_{fs}} = \mathbf{-Q}$ and $\mathbf{M_{fs}} = \boldsymbol{\rho_w\, Q^T}$. Equation (3) expresses a second order linear differential equation having unsymmetrical matrices and can be solved by means of direct integration methods.

5 MODELING AND ASSUMPTIONS

In the present study, in order to satisfy the continuity conditions between the fluid and solid media at the boundaries. The nodes at the common lines of the fluid and the plane elements are constrained to be coupled in the direction normal to the interface. Relative movements are allowed to occur in the tangential directions. This is implemented by attaching the coincident nodes at the common lines of the fluid and the plane elements in the normal direction. At the interface of the fluid-structure system, only the displacements in the direction normal to the interface are assumed to be compatible in the structure as well as the fluid. The fluid is assumed to be linear-elastic, incompressible, irrotational and nonviscous. A typical concrete gravity dam is chosen as a case study. The dam is 110 m high and its thickness varies from 10 m at the crest to 100m at the foundation level. 2-D finite element model is implemented via ANSYS code version 14 [18]. No absorption is considered at reservoir bottom. The depth of the reservoir is considered 100 m. Since the extent of the reservoir is large, it is necessary to truncate the reservoir at a sufficiently large distance from the dam. A length of reservoir equivalent to two times its depth is chosen for adequate representation of hydrodynamic effects on the dam body. The depth of foundation of 150 m is taken into account in the calculations. The dam and foundation materials are assumed to be linear-elastic, homogeneous and isotropic. A two dimensional (2D) finite element model (PLANE 182) is used to model dam body and foundation soil. A two dimensional (2D) finite fluid element model (FLUID 29) is used to model the reservoir water. The employed Finite Element mesh is shown by Figure 2. The effect of foundation flexibility has been obtained by considering four dam-foundation rock interaction ratios i.e. modulus of elasticity of foundation to modulus of elasticity of dam E_f/E_c= 0.5, 1, 5 and 500.

6 MATERIAL PROPERTIES & LOADING HISTORY

The material properties for the concrete gravity dam, foundation soil and reservoir water are presented as follows:

Table 1. Material Properties

Mass Concrete	Isotropic Elasticity	24 GPa
	Poisson's Ratio	0.2
	Density	2400 Kg/m^3
Foundation Rock	Isotropic Elasticity	24 GPa
	Poisson's Ratio	0.33
	Density	2400 Kg/m^3
Reservoir Water	Density	1000 Kg/m^3
	Wave Velocity	1440 m/s
	Wave Reflection	1.0

The selected gravity dam is simulated including dam-reservoir-foundation interaction using the Finite Element discretization shown in Figure 2. Linear transient dynamic analysis adopted in ANSYS code version 14 is implemented. In order to investigate the effects of dam-water-foundation on the time history response of gravity dams, the linear earthquake response of the selected dam is determined for the specified case. A static analysis is initially implemented and then, the dam is subjected to the El-Centro N–S record of Imperial Valley earthquake (1940) shown in Figure 3 in upstream-downstream direction.

7 NUMERICAL RESULTS & DISCUSSIONS

Numerical results for the seismic response of dam-reservoir-foundation interaction shown by Tables 2 to 4 and Figures (4) to (14) are discussed in the following sections. Analysis of the effect of foundation flexibility on seismic response of concrete gravity dams is performed for four values of foundation flexibility ratio E_f/E_c =0.5, 1, 5 and 500, where E_f refers to foundation modulus of Elasticity while E_c refers to concrete modulus of elasticity. In the present analysis, the ratio of E_f/E_c =500 represents very rigid foundation while the ratio of E_f/E_c = 0.5 assigns for very flexible foundation.

7.1. Effect of Foundation Flexibility on Gravity Dam Displacement

Maximum horizontal crest, toe and heel displacements for all ratios of E_f/E_c are summarized in Table 2 and Figure (4). It is clear that the effect of foundation flexibility on dam displacements is significant for E_f/E_c ranges between 0.5 and 5 while no significant effect for ratios greater than 5 is observed. Maximum horizontal crest displacement is 9.369 cm for E_f/E_c =0.5 while least displacement equals 2.809 cm for E_f/E_c = 500. Figure (5) shows a typical time history for horizontal crest displacement for E_f/E_c =1. Maximum horizontal dam base displacement follows the preceding analysis of crest displacement. Maximum horizontal toe displacement is 3.144 cm for E_f/E_c =0.5 while least displacement equals 0.0000174 cm for E_f/E_c = 500. Figure (6) shows a typical time history for horizontal dam toe displacement for E_f/E_c =0.5. Maximum horizontal heel displacement is 3.233 cm for E_f/E_c =0.5 while least displacement equals 0.0000225 cm for E_f/E_c = 500. Figure (7) shows a typical time history for horizontal dam heel displacement for E_f/E_c = 5. Results indicate that the foundation flexibility has a significant impact on dam displacements. Maximum displacements are associated with ratios of E_f/E_c less than unity (E_f/E_c =0.5), while least displacements are obtained for very rigid foundation (E_f/E_c =500).

Table 2. Results for Maximum Dam Displacement

E_f/E_c	Max. Horizontal crest displacement m	Max. Dam toe horizontal displacement m	Max. Dam heel horizontal displacement m
0.5	0.09369	0.03144	0.03233
1	0.05928	0.01285	0.01389
5	0.03351	0.00188	0.00230
500	0.02809	0.0000174	0.0000225

7.2. Effect of Foundation Flexibility on Dam Stresses

Results for maximum principle, normal and shear stresses at both dam toe and dam heel for all ratios of E_f/E_c are summarized in Table 3 and Figures (8) and (10). It is clear that the effect of foundation flexibility on dam stresses is significant for E_f/E_c ranges between 0.5 and 5 while this effect decreases significantly for values greater than 5. For the present case study of full reservoir, maximum stresses are developed at dam toe as shown by Table 3. Figure (8) shows that maximum principal stress at dam toe is -3425.2 KPa for E_f/E_c =0.5 while least stress equals -1158.6 KPa for E_f/E_c = 500. Figure (9) shows a typical time history for principal stress at dam toe for E_f/E_c =1. Figure (10) shows that maximum normal stress at dam heel is -1778.9 KPa for E_f/E_c =0.5 while least stress equals -1067.3KPa for E_f/E_c = 500. In addition, Figure (10) shows that maximum shear stress at dam heel is -750.33 KPa for E_f/E_c =0.5 while least stress equals -462.41 KPa for E_f/E_c = 500. Figures (11) shows a typical time history for normal stress at dam heel for E_f/E_c =0.5 while Figure (12) shows a typical time history for shear stress at dam heel for E_f/E_c = 5. Results indicate that the foundation flexibility has a significant impact on dam stresses. Maximum stresses are associated with ratios of E_f/E_c less than unity (E_f/E_c =0.5), while least stresses are obtained for very rigid foundation (E_f/E_c =500).

Table3. Results for Maximum Stresses

E_f/E_c	Stress at toe			Stress at heel		
	Max. Principal KPa	Max. Normal KPa	Max. Shear KPa	Max. Principal KPa	Max. Normal KPa	Max. Shear KPa
0.5	-3425.2	-8200.6	-3710.3	-2347.44	-1778.9	-750.33
1	-2563.5	-5405.7	-2552.8	-2051.3	-1511.1	-679.48
5	-1490.55	-2318.0	-1124.9	-1433.8	-1050.7	-532.46
500	-1158.6	-1527.3	-692.49	-1132.6	-1067.3	-462.41

7.3. Effect of Foundation Flexibility on Hydrodynamic Pressure

Results for the effect of foundation flexibility on hydrodynamic pressure for all ratios of E_f/E_c are summarized in Table 4 and Figures (13) to (15). It is clear that foundation flexibility has no significant effect on hydrodynamic pressure for all ratios of E_f/E_c.. Figure (13) shows the time history of hydrodynamic pressure at dam base for E_f/E_c= 1. Figure (14) shows the time history of hydrodynamic pressure at 80% of reservoir depth for E_f/E_c =5. . Figure (15) shows the time history of hydrodynamic pressure at 50% of reservoir depth for E_f/E_c =500. For all ratios of E_f/E_c, the results are the almost the same. This result can be explained as the hydrodynamic pressure is mainly a function of the reservoir height and the earthquake severity which are the same for all ratios. The presence of foundation in dam modeling does not affect significantly the hydrodynamic pressure..

Table 4. Results for Maximum Hydrodynamic Pressure in KPa

E_f/E_c	At dam base	At 0.80 H	At 0.50 H
0.5	-195.203	-43.9589	-15.7018
1	-195.203	-43.9589	-15.7018
5	-195.203	-43.9589	-15.7018
500	-195.203	-43.9589	-15.7018

8 CONCLUSIONS

The present work is an attempt to assess the effect of flexibility of the foundation on the seismic response of a concrete gravity dams. Results indicate that the foundation flexibility has a significant impact on dam stresses. Maximum displacement and stresses are associated with foundation flexibility ratios E_f/E_c less than unity, while least responses are obtained for very rigid foundation with E_f/E_c=500. Results assure that in simulating dam-reservoir–foundation interaction problems, the ratio of E_f/E_c =500 can be recommended to represent the case of fixed foundation with an acceptable accuracy. Results assign that flexibility of foundation has almost no significant effect on hydrodynamic pressure.

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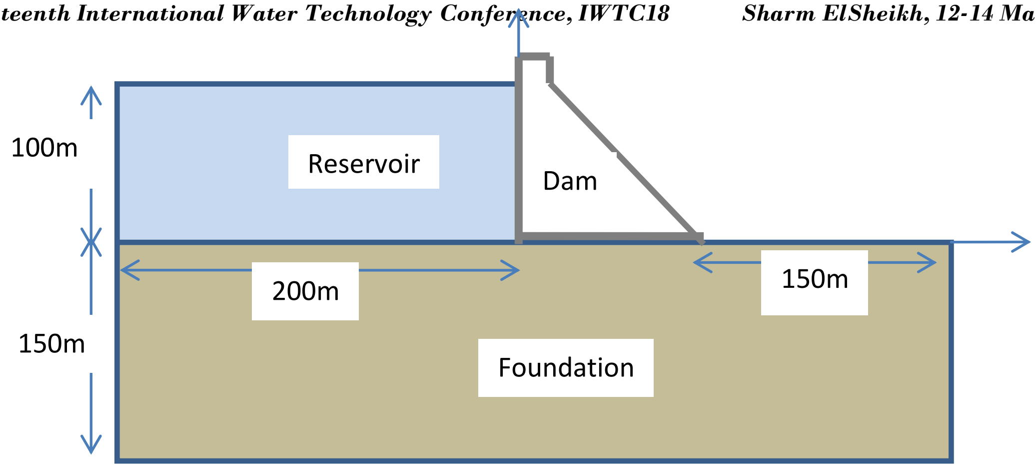

Figure 1. Dam-Reservoir-Foundation Idealization

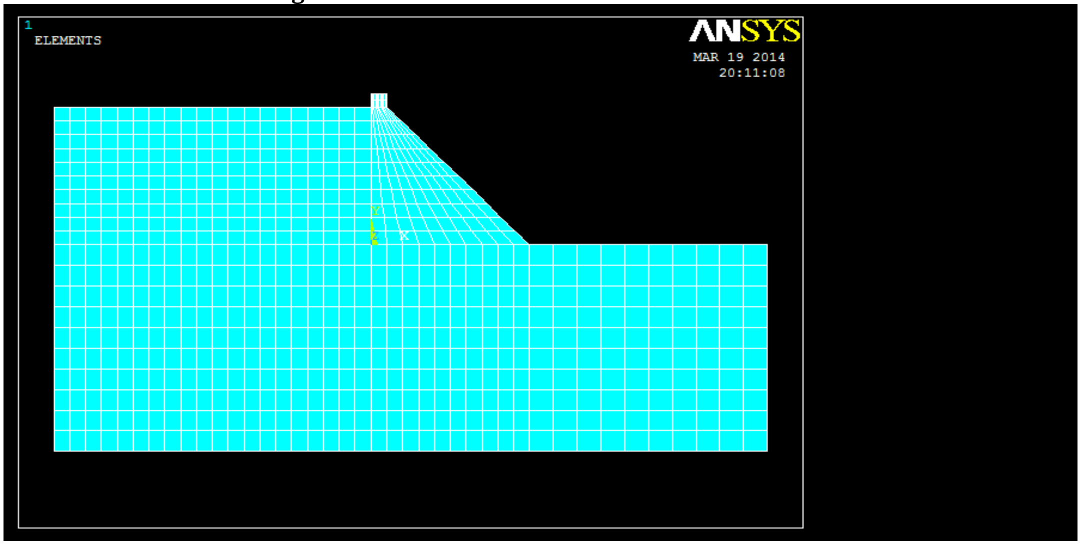

Figure 2. Finite Element Mesh for dam-reservoir-foundation model

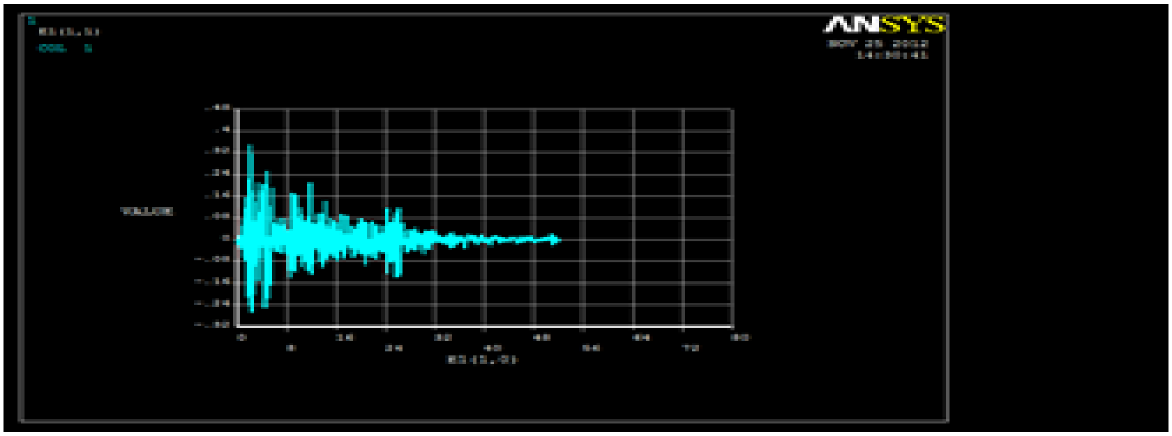

Figure 3. Horizontal Acceleration record of the El-Centro earthquake

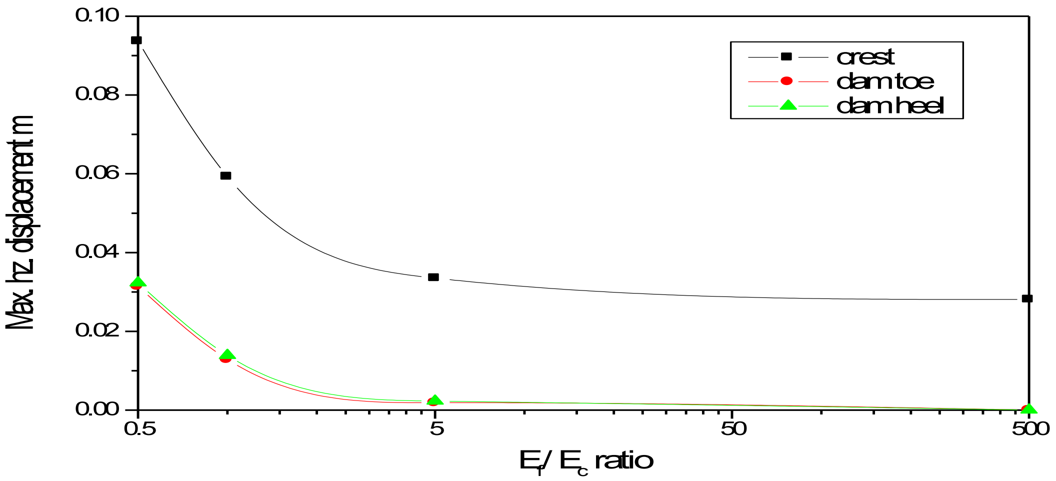

Figure 4. Effect of Foundation Flexibility on Gravity Dam Displacements

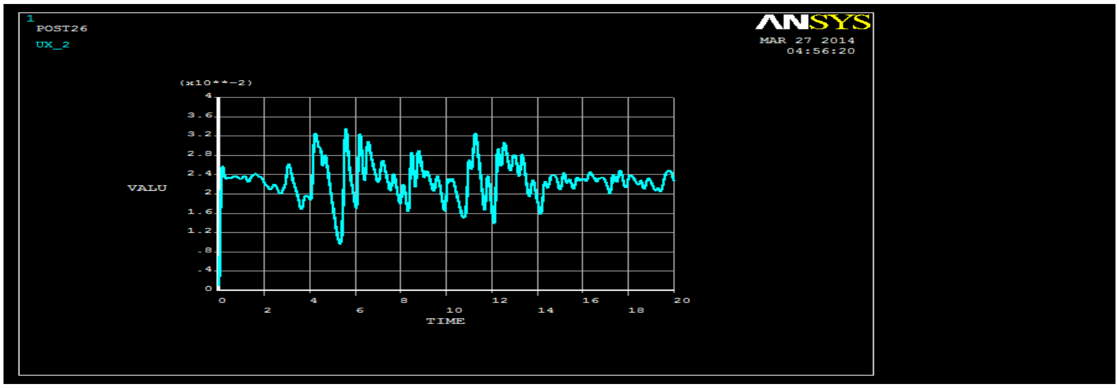

Figure 5. Time History for Horizontal Crest Displacement for E_f/E_c=1.

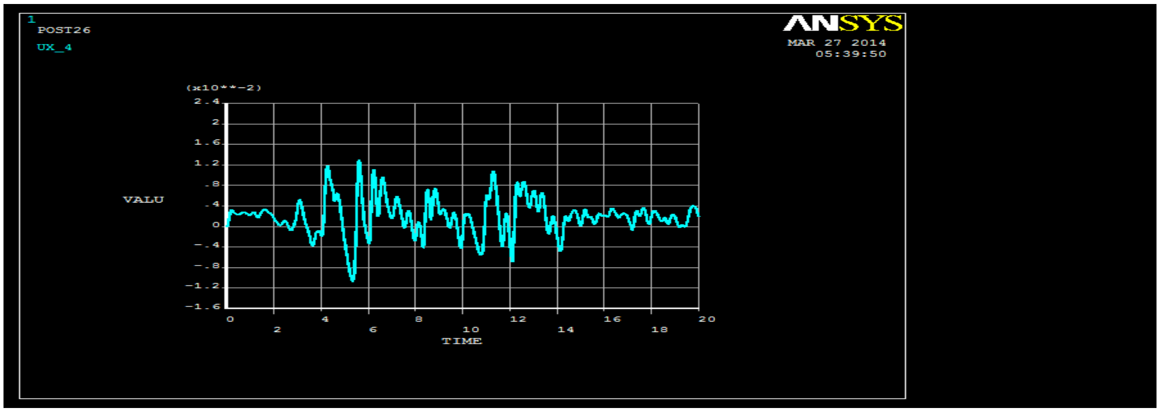

Figure 6. Time History for Horizontal Dam Toe Displacement for E_f/E_c= 0.5

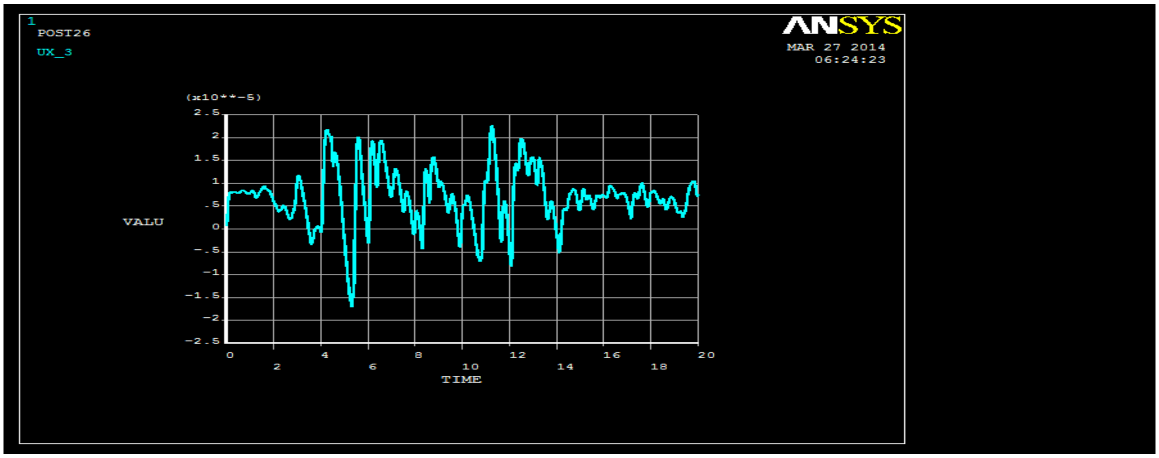

Figure 7. Time History for Horizontal Dam Heel Displacement for E_f/E_c= 5.

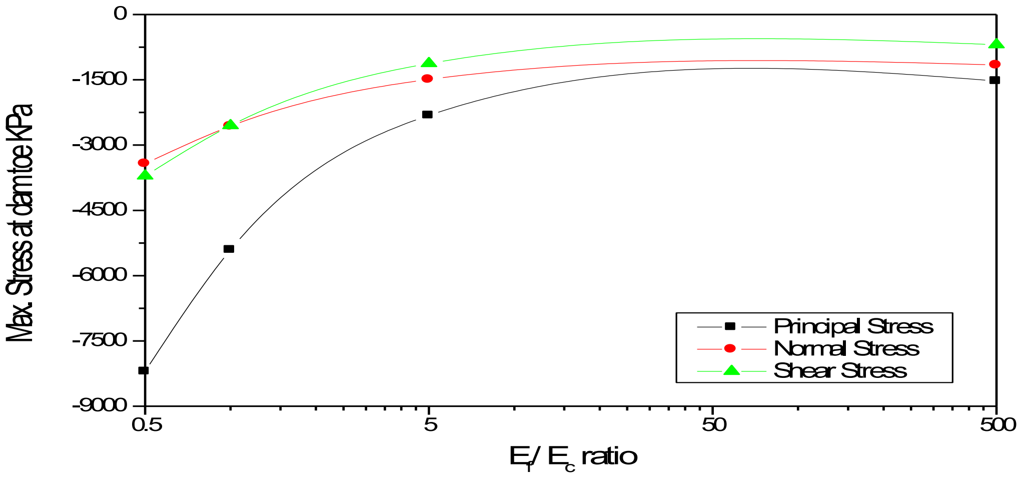

Figure 8. Effect of Foundation Flexibility on Stresses at Dam Toe

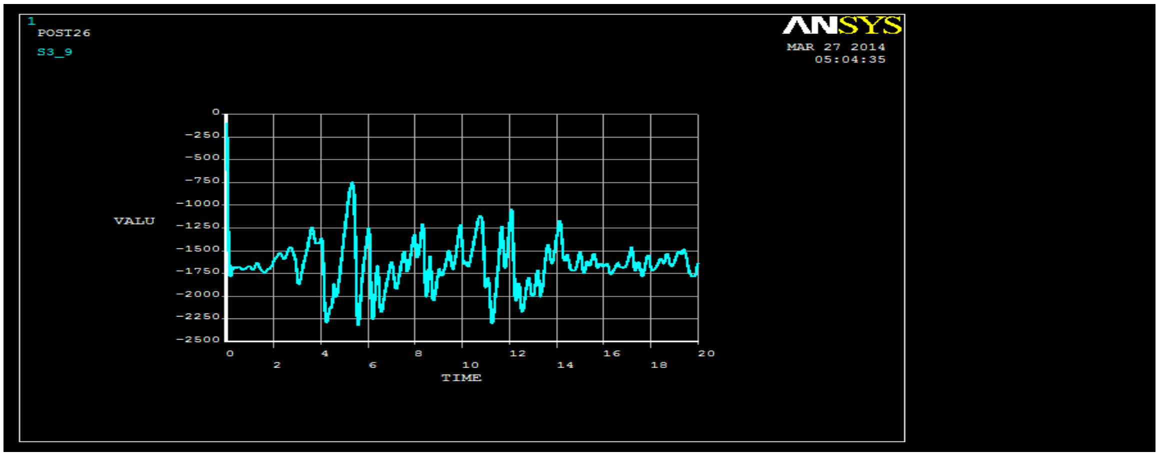

Figure 9. Time History for Principal Stress at Dam Toe in KPa for E_f/E_c=1

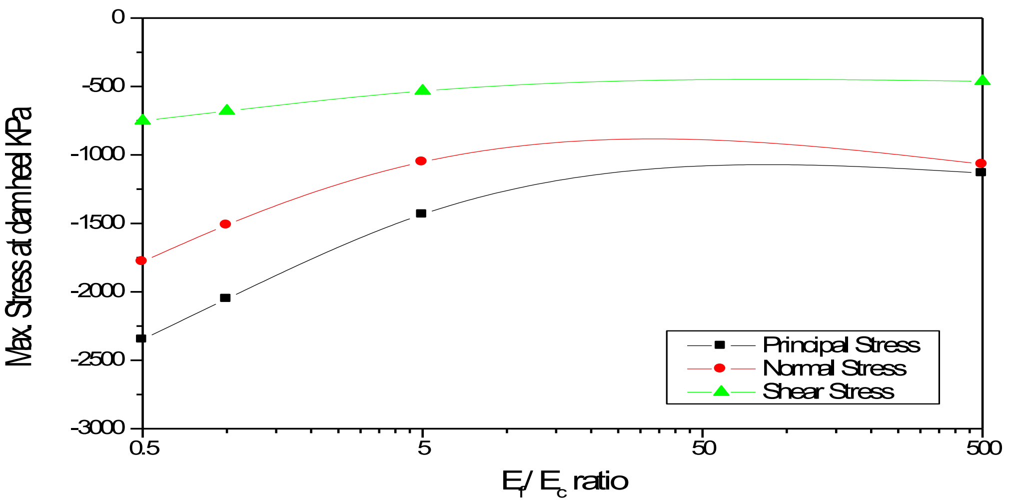

Figure 10. Effect of Foundation Flexibility on Stresses at Dam Heel

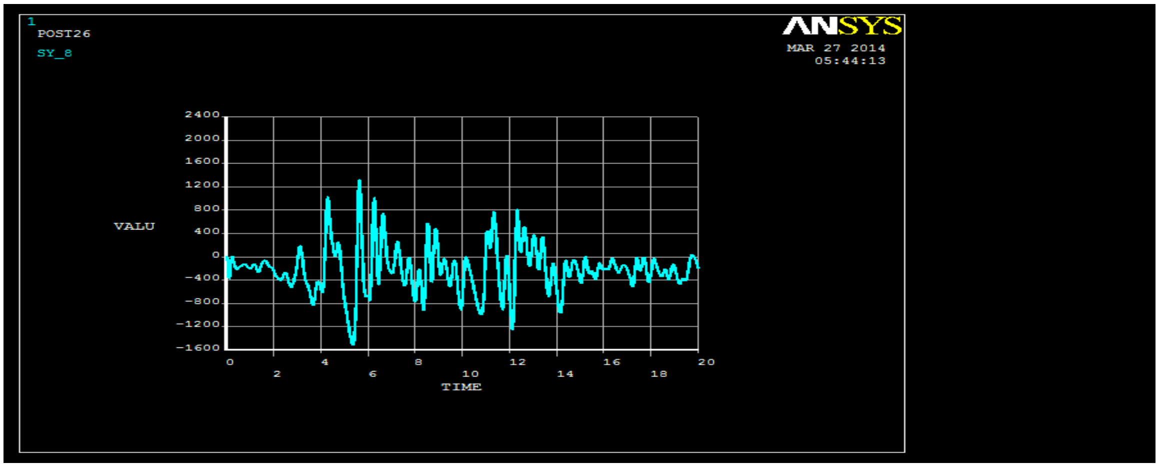

Figure 11. Time History for Normal Stress at Dam Heel KPa for E_f/E_c=0.5

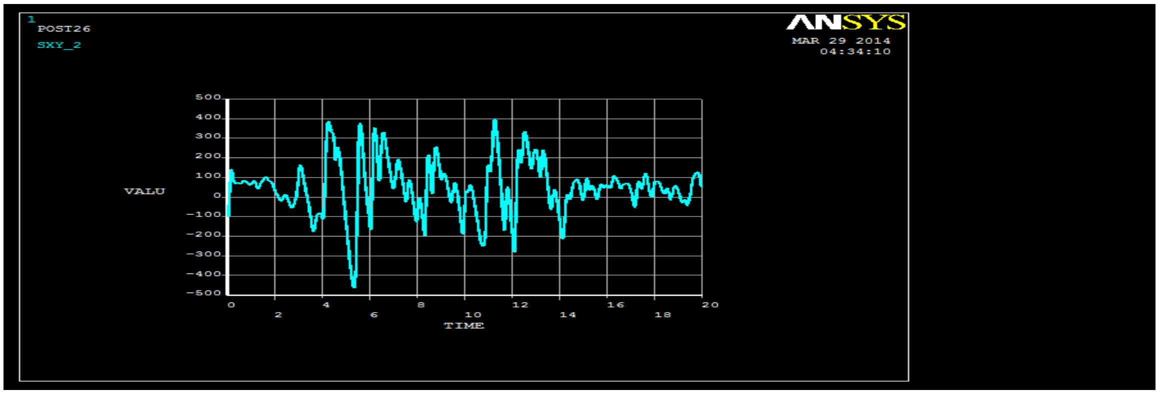

Figure 12. Time History for Shear Stress at Dam Heel for E_f/E_c= 5

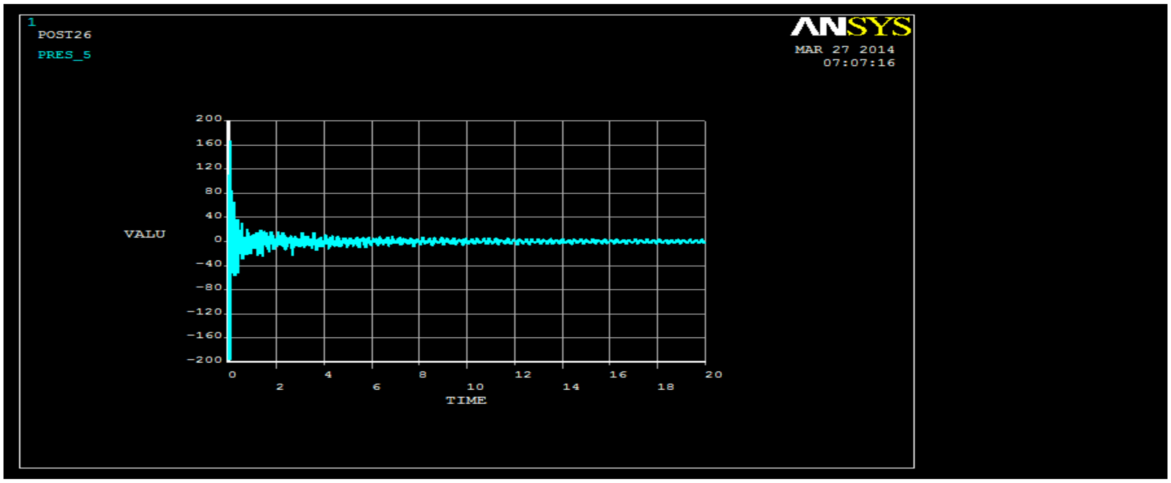

Figure13. Time History for Hydrodynamic Pressure at dam heel for E_f/E_c= 1

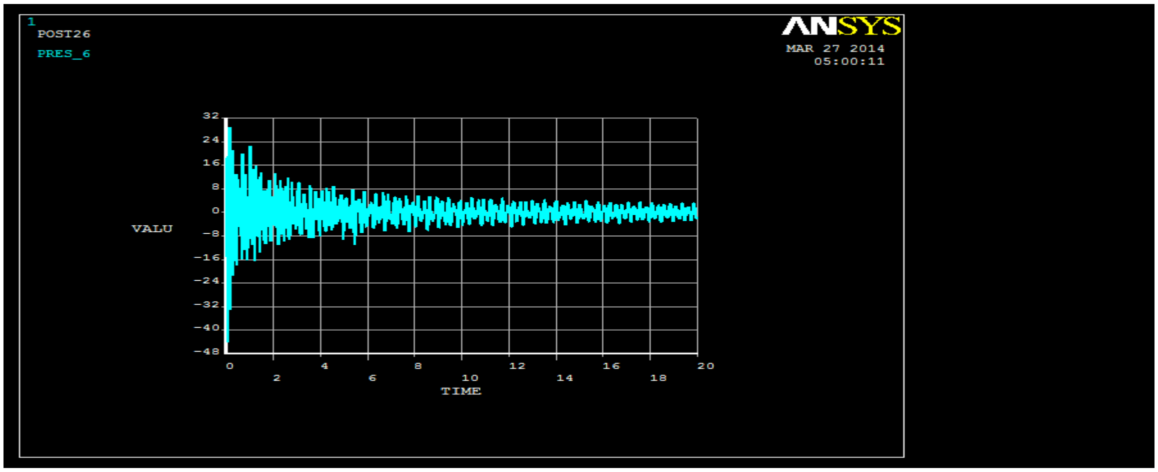

Figure14. Time History for Hydrodynamic Pressure at 0.8 of reservoir depth for E_f/E_c=5

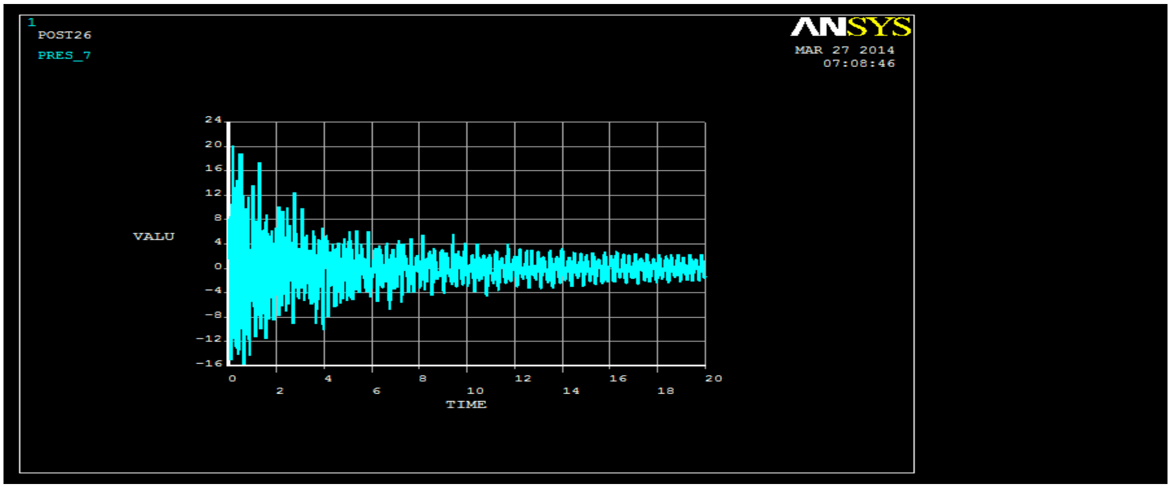

Figure15. Time History for Hydrodynamic Pressure at 0.5 of reservoir depth for E_f/E_c=500