ANALYSIS OF INFINITE RESERVOIR SUBJECTED TO EARTHQUAKE EXCITATION

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This foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant it's acceptable as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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I, REHAN AHMED, Master of Engineering in Civil Engineering (Structural Engineering), Jadavpur University, Faculty of Engineering and Technology, hereby declare that the work being presented in the thesis work entitled, "ANALYSIS OF INFINITE RESERVOIR SUBJECTED TO EARTHQUAKE EXCITATION", is an authentic record of work that has been carried out in the Department of Civil Engineering, Jadavpur University, Kolkata under **Mr. SANTOSH KUMAR DAS**, Assistant Professor, Department of Civil Engineering, Jadavpur University. The work contained in this thesis has not yet been submitted in parts or full to any other university or institute or professional body for award of any degree or diploma or any fellowship.

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SYNOPSIS

Dam hold huge amount of water. Retained water is used for flood controlling, irrigation and hydroelectricity generation. Accurate estimation of hydrodynamic pressure on Dam is major issue in design of dam. Conventional approach becomes very complex in case of analysis structure having irregular geometry such as Dam. Finite element analysis is the best solution for this issue. Displacement-based approach for modeling of fluid medium may create some spurious mode which has no practical meaning. To overcome this problem Eulerian approach is used for determination of hydrodynamic pressure. In this pressure based approach number of nodal unknown parameter is reduced. Determination of hydrodynamic pressure on concrete gravity dam becomes very difficult due to infinitely extended length of reservoir. To remove this difficulty, the reservoir is truncated at a finite distance from face of dam. Truncation of reservoir also reduces the computational time. For simplification of analytical procedure, the reservoir bottom is assumed as rigid which does not represent actual behavior of the system. Such assumption overestimates the value of hydrodynamic pressure because a part of energy of hydrodynamic waves gets absorbed in sediment deposited at bottom of reservoir. Most of the analysis has been done considering vertical dam reservoir interface. The dam reservoir interface may be inclined in practical scenario. Inclination of dam reservoir interface largely affects the value of hydrodynamic pressure.

In present analysis, fluid is considered as non-viscous and linearly compressible. Bottom absorption effect is taken into consideration. Reservoir is truncated at certain distance away from structure to reduce the computational time. Eulerian approach is used to determine the hydrodynamic pressure at face of dam. Finite element method is employed to discretize the reservoir medium. Surface wave is neglected. Dam reservoir interface is considered as inclined to get accurate value hydrodynamic pressure. The analysis is restricted to two dimensional. A MATLAB code is developed for analysis purpose. Hydrodynamic pressure distribution and time history analysis is obtained for harmonic excitation. Again time history plot also obtained for earthquake excitation.

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CHAPTER 1

INTRODUCTION

Dam is a structure which is built across a stream or river to hold huge amount of water. Dam is very useful for cultivation, flood controlling and generation of hydropower. Failure of dam is dangerous for human Life and property. Hence, high level of accuracy is required for design and analysis of such structure. Hydrodynamic pressure generated at the face of dam due to adjacent reservoir at the time of earthquake. Proper study on hydrodynamic pressure is very much important. Geometrical property and behavior of adjacent reservoir influence the hydrodynamic forces on dam. So, thorough study of different parameters of reservoir is required for determination of hydrodynamic pressure.

Finite element technique is generally used to model the dam and reservoir system. Unbounded reservoir is truncated to a suitable distance to reduce the computational time. Application of appropriate nonreflecting boundary condition along the truncated face is very much important. Reservoir bottom absorption coefficient is also an important parameter for determination of hydrodynamic pressure. Inclination of dam-reservoir interface, height of reservoir and truncated length are different parameters influencing the hydrodynamic pressure. In the present study eight node isoparametric elements is used to discretize the two dimensional geometry of reservoir. Pressure is considered as nodal unknown parameter. Dam is considered to be rigid. Fluid is considered as non-viscous and compressible. A suitable nonreflecting boundary condition is implemented at truncation surface of reservoir. Reservoir bottom absorption is included for analysis purpose. Hydrodynamic pressure distribution is obtained at the face of dam for different height of reservoir. Nature of hydrodynamic pressure distribution is also obtained for different inclination of dam- reservoir interface. The pressure is determined by applying harmonic and as well as earthquake excitation. A MATLAB code is developed for analysis purpose. Newmark’s time integration method is applied to solve the dynamic equilibrium equation.

REVIEW OF LITERATURE

G. FENVES AND A.K. CHOPRA (1984) proposed a sub-structure method for analysis of hydrodynamic pressure of dam-reservoir interface considering flexible foundation rock. In this study the effect of sediment at the bottom of reservoir was also taken into consideration. The dam-reservoir system was considered as two dimensional systems and behavior was assumed to be linear. An earthquake analysis was carried out to verify the results of the solution. Computational time for different cases was noted and the conclusion was made that computational time required for bottom absorption effect was very less.

X.LI ET AL. (1995) proposed finite element analysis of dam-reservoir system using far boundary condition. A reservoir with constant depth and flexible foundation was considered to develop a nonlocal relation between velocity potential and its derivative on far boundary condition. The proposed far boundary condition has comparatively more number of parameter and it has also number of series of term which control the numerical accuracy of the obtained results. It is very efficient for un deformed and deformed dams. This study can also be effectively extended to use for three dimensional and time domain analyses.

D. MAITY AND S.K. BHATTACHARYYA (1998) proposed time domain analysis of dam reservoir system using far boundary condition. In this method the infinite fluid domain is truncated to make it finite one. Complete system of dam and reservoir is discretized using finite elements technique. Pressure was assumed to be the only nodal unknown parameter. Fluid was considered as compressible. Classical wave equation was used to derive the truncation boundary condition. Negligible additional computational effort is required for proposed truncation boundary condition. The accuracy of far boundary condition was checked, using finite element method, by comparing with existing literature. An effective and simple boundary condition was developed to model the reservoir. It gives accurate result even when the truncation boundary is located very small distance from the structure.

M. GHAEMIAN ET.AL (1999) developed staggered solution method to analyze dam-reservoir interaction in time domain. Smeared Analysis method based on nonlinear mechanic's crack propagation was used to study the cracking and response of dam. The predicted crack pattern is different from that of the case when the dam–reservoir interaction is approximated using the added mass approach. It is concluded that proper modelling of the dam–reservoir interaction is important in the nonlinear response analysis of concrete gravity dams.

D. MAITY AND S.K BHATTACHARYYA (2005) executed finite element analysis of the fluid–structure systems considering the coupled effect of elastic structure and fluid. The equations of motion of the fluid were expressed in terms of the pressure variable alone. The fluid was considered as non-viscous and incompressible. The elastic structure and the fluid domain were treated as two separate systems. The solution of the coupled system was done by solving the two systems separately. Developed iteration scheme was used to find Non-divergent pressure and displacement simultaneously through a few numbers of iterations. The proposed algorithm was validated comparing with the existing literature. The parametric study of the coupled system showed the importance of fluid height and material property of the structure.

S. KUCUKARSLAN (2005) Applied finite element approach for analysis of a vibrating structure in an unbounded and incompressible and inviscid fluid including dam–reservoir interaction. In the derivation of boundary condition, it was assumed that vibration of dam was in the normal direction of dam–reservoir interface and this interface is vertical. Moreover, bottom of fluid was rigid and horizontal. In the finite element formulation, unbounded domain of reservoir arose a problem in modeling. To achieve this difficulty, the unbounded domain should be truncated at a certain distance away from the structure. An exact boundary condition along the truncating surface of an unbounded reservoir domain was developed by approximating the analytical solution of the hydrodynamic pressure. A numerical study was done to compare the results of boundary conditions of Sommerfeld and Sharan.

I. GOGOI AND D. MAITY (2006) proposed an efficient truncation boundary condition including bottom absorption effect. The value of the hydrodynamic pressure affected due to bottom absorption effect is considered. Sediment present at the bottom of the reservoir absorbs the hydrodynamic wave that certainly affects the value of hydrodynamic pressure. Most of the previous literature did not consider the bottom absorption effect and angle of inclination of dam reservoir interface. This study presented a proper finite element method to find out the hydrodynamic pressure considering bottom absorption effect and inclination of dam-reservoir interface. The proposed method can easily implement to find truncation boundary coefficient.

A. SAMII AND V.LOTFI (2007) proposed two different modal approaches for dynamic analysis of concrete gravity dam–reservoir systems. Two different modal approaches are coupled and decoupled modal method. In case of coupled modal technique calculation of modes involves some complications due to its corresponding unsymmetrical Eigen problem. Response can be efficiently obtained in each step of coupled modal method. But on the other hand responses are easily determined by standard eigenvalue solvers in decoupled modes of system. The equation of motion is also solved very efficiently in this approach. Both the methods are also used to analyse a typical dam-reservoir system to check the accuracy and efficiency of the methods.

C. BIRK AND P. RUGE (2007) presented a method to solve dam–reservoir interaction problem which was directly in the time-domain by modeling a part of the reservoir as a semi-infinite fluid-channel. Radiation damping was taken into account rigorously using an analytical solution with respect to the direction of wave propagation. The key step of the method consists of approximating the resulting modal flux–pressure relationship by a rational function, which can be replaced by a system of linear equations in the frequency-domain. They contributed an enhanced approximation algorithm based on an iterative solution of the nonlinear optimization problem had been suggested. The system of first-order differential equations can be coupled to the finite element equations of the bounded part of the system. The total dam–reservoir system can then be analyzed directly in the time-domain. The proposed concept requires a constant cross-section of the semi-infinite fluid-channel, corresponding to parallel fluid-layers resulting from the semi-discretization. In order to increase the applicability of the method, a description of the semi-infinite fluid region using polar coordinates, or more general scaled boundary coordinates, was desirable.

M. PASBANI-KHIAVI ET AL. (2008) developed a finite element method to analyze dam-reservoir system. The fluid was assumed to be non-viscous and incompressible. Bottom of the reservoir is assumed to be rigid and horizontal. The dam reservoir interface is considered as vertical. Governing equation was implemented for vertical and horizontal earthquake component. Finite element model was developed using Galerkin's Method with eight nodded elements. Sommerfeld boundary condition and perfect damping boundary condition are applied at truncation boundary using proposed model. The results of the both boundary conditions are compared with the analytical results. It can be concluded that the proposed boundary condition gives the accurate result for both Somerfield and perfect damping boundary condition. It is also concluded that the distance of truncation surface should be twice or more than the depth of the reservoir for more accuracy.

M.BOUAANANI AND FEI YING LU (2009) used potential based fluid finite element formulation to analyze earthquake excited dam-reservoir system. Frequency and time domain analysis were performed to validate potential based finite element method. Fluid structure interaction and reservoir bottom absorption effects were illustrated with the help dynamic response of system. They also presented a case study of typical dam-reservoir interaction subjected to earthquake excitation to validate the proposed potential based finite element formulation.

M. A. GHORBANI AND M. PASBANI-KHIAVI (2011) used finite element method to analyze the dam-reservoir system considering the fluid to be incompressible non viscous and irrotational. Bottom of the reservoir was considered as rigid and horizontal. Weighted residual standard Galerkin method with eight node finite elements was used to analyze the dam reservoir system by developing a symmetric matrix equation. Finite element code was developed considering only the vertical and horizontal earthquake component. A new boundary condition was developed at truncation surface for infinite fluid to show that the energy get dissipated in the reservoir in infinite upstream direction through radiation. Perfect damping boundary condition was developed using the proposed model. The results of both the boundary conditions were compared with the analytical results to check the accuracy of the method. It was concluded that both the method gives accurate result and it can be generalized for any boundary condition.

N.P. GAHLOT AND A.R. GAJBHIYE (2013) presented the methods of seismic analysis of dam. This paper deals with a case study of Totaladoh Dam situated in Vidarbha of Maharashtra for seismic analysis by IS code method. The Results obtained by this method was compared with the results obtained by finite element method in IS code method stress analysis was done considering the dam cross section as a cantilever beam of variable thickness. A finite element procedure was developed for seismic analysis of dam. In this proposed model vertical and cross stream component of pressure was considered and water was considered to be compressible.

I. D. ERHUNMWUN AND J. A. AKPOBI (2017) suggested finite element technique to determine well pressure distribution of a boundless reservoir. The diffusivity equation was used to analyze the pressure distribution of reservoir. Finite element technique was employed to carry out the analysis over the cross-section of the reservoir. Assumption was made that the pressure distribution of the reservoir was uniform. The accuracy of the result was validated comparing with Chatas and Lee. The comparison shows a strong positive correlation between the two methods. It was seen that the dimensionless pressure decreases from the well bore to the external boundary.

I. ROZAINA ET AL. (2017) proposed the finite element technique for earthquake analysis of concrete dam to study the performance and behavior of the dam. LUSAS 14.3 computer program was used to implement the procedure. 5 modes of shape for dam were utilized considering linear dynamic analysis of concrete dam. Sg. Kinta Dam was analyzed in this study. The results of stress behavior obtained from the study do not exceed the allowable stress capacity. The normal stress and share stress obtained was 221.248KN/m^2 and 436.499KN/m^2 which was less then allowable stress capacity of 800KN/m^2. Maximum displacement also gives the satisfactory results. Maximum displacement obtained from this analysis was 3.48mm in the mode shape 5. The result obtained from this study show that LUSAS 14.3 is capable for seismic analysis of concrete gravity dam.

Y. Y. WANG ET.AL (2017) used scaled boundary finite element method, finite element method and infinite element method to model the system of reservoir. Scale boundary finite element method (SBFEM) was used to find the water pressure of upstream face of dam. The effect of radiation damping on foundation of the reservoir was considered in this study. The dynamic water pressure on the upstream of the dam was calculated considering Koyna gravity dam. The time history of seismic displacement and response of dam for different elastic modulus were obtained. By comparing the displacement result of infinite element model for different elastic modulus, it was concluded that the response of dam increases with the increase of elastic modulus. The dynamic water pressure was calculated by SBFEM. The finite element method was used to model the infinite reservoir. This study shows that SBFEM can be effective and convenient for the analysis of water and dam interaction.

MOHSEN ET.AL (2018) developed two methods for analysis of dam-reservoir system. The methods are far field boundary condition and domain reduction method (DRM). Concrete gravity dam is one of the important structures all over the globe. Behavior of dam due to earth quake is one of the important aspects of engineering field. Safety of the dam in presence of seismic force is one of the important tasks now days in engineering field. For accurate analysis for dam-reservoir system some important factor like mass and seismic wave input should be taken into consideration. In this study the displacement and stresses results obtained from these methods are also verified with EAGD-84 program. It is concluded that the results obtained from both the methods are accurate for modeling mass foundation of dam-reservoir system.

A. LØKKE AND A.K. CHOPRA (2019) developed the direct FE method for 2D dam–water–foundation systems. Step-by-step procedures are presented for computing far earthquake analysis of 2D free-field systems. The procedure is validated by computing frequency response functions and transient response of an idealized dam–water–foundation system. This direct FE method is generalized to 3D systems. Effective earthquake forces can be computed from the boundaries of the free-field systems. This system requires extensive book-keeping and data transfer for large 3D models. To reduce these requirements convenient simplifications of the procedure are proposed and their effectiveness demonstrated. Practical modeling was considered for two of the most influential aspects of these analyses: nonlinear mechanisms and energy dissipation (damping). The findings have vast application for modeling of energy dissipation and calibration of damping values for concrete dam analyses.

H. MOHAMMADNEZHAD ET.AL (2019) proposed an appropriate direct finite element method to simulate the mass radiation damping and wave propagation using ABAQUS. Far field boundary condition is used to model semi-infinite reservoir subjected to earthquake. The result obtained from the software is verified with analytical results. The results for massed and massless foundation were also verified using EAGD-84 program. It is concluded that the massless foundation approach leads to overestimation of displacement and stress. This overestimation leads to higher unnecessary expenses for new dam construction. Thus mass of foundation should be taken into consideration during the construction of new dam.

V. SHARMA ET.AL (2019) presented a space-time finite element method for the seismic analysis of dam-reservoir-soil system. A first order time derivative of hydrodynamic pressure is introduced as primary unknown. Displacement and pressure are considered as secondary unknown. These secondary unknowns are computed by consistent time integration of first primary unknowns. This system results in number of algebraic expression which can be solved using block iterative algorithm. In each step of algorithm two system of linear equation one for velocity field and another for auxiliary field are solved separately and they are coupled in next iteration. Method was verified by solving benchmark dam-reservoir system. It is observed that very little iteration is required for convergence. Finally, the method was used to analyze the effect of earthquake on dam-reservoir system.

R.Y. AHMAD AND B. AHMET (2021) developed a reliable finite element method to stimulate mechanical interaction between structure-foundation-reservoir and discretized these regions. The reservoir region which incorporates the compressibility effect and surface sloshing motion of water is formulated by two- dimensional Lagrangian fluid finite elements. The dynamic responses of the structure under a given ground motions are obtained in three conditions: structure-reservoir interaction with rigid foundation, structure-reservoir interaction with finite region of flexible foundation and structure-reservoir interaction with including the infinite region of flexible foundation. During dynamic analysis, only the radiation conditions toward infinity and energy dissipation in foundation is simulated considering infinite elements in the infinite region of the flexible foundation. The results of dynamic analysis obtained from structure - foundation-reservoir interaction are shown without considering the radiation conditions in the infinite region of the constant depth reservoir. And only the static and dynamic displacement responses of the crest are given in this paper. All steps of static and dynamic analysis are performed using FORTRAN 90 coding language. The static and dynamic responses are validated and compared with the results of other research papers.

THEORITICAL FORMULATION

Reservoir geometry is considered as two dimensional. Fluid is considered as non-viscous and linearly compressible. The hydrodynamic pressure distribution of the reservoir is determined from following pressure wave equation:

$$\nabla^2 p(x,y,z) = \frac{1}{c^2}\ddot{p}\,(x,y,t) \qquad (1)$$

Where c is wave velocity, *x* and *y* are space variable, *p* (x, y, t) is hydrodynamic pressure, '*t*' is time variable.

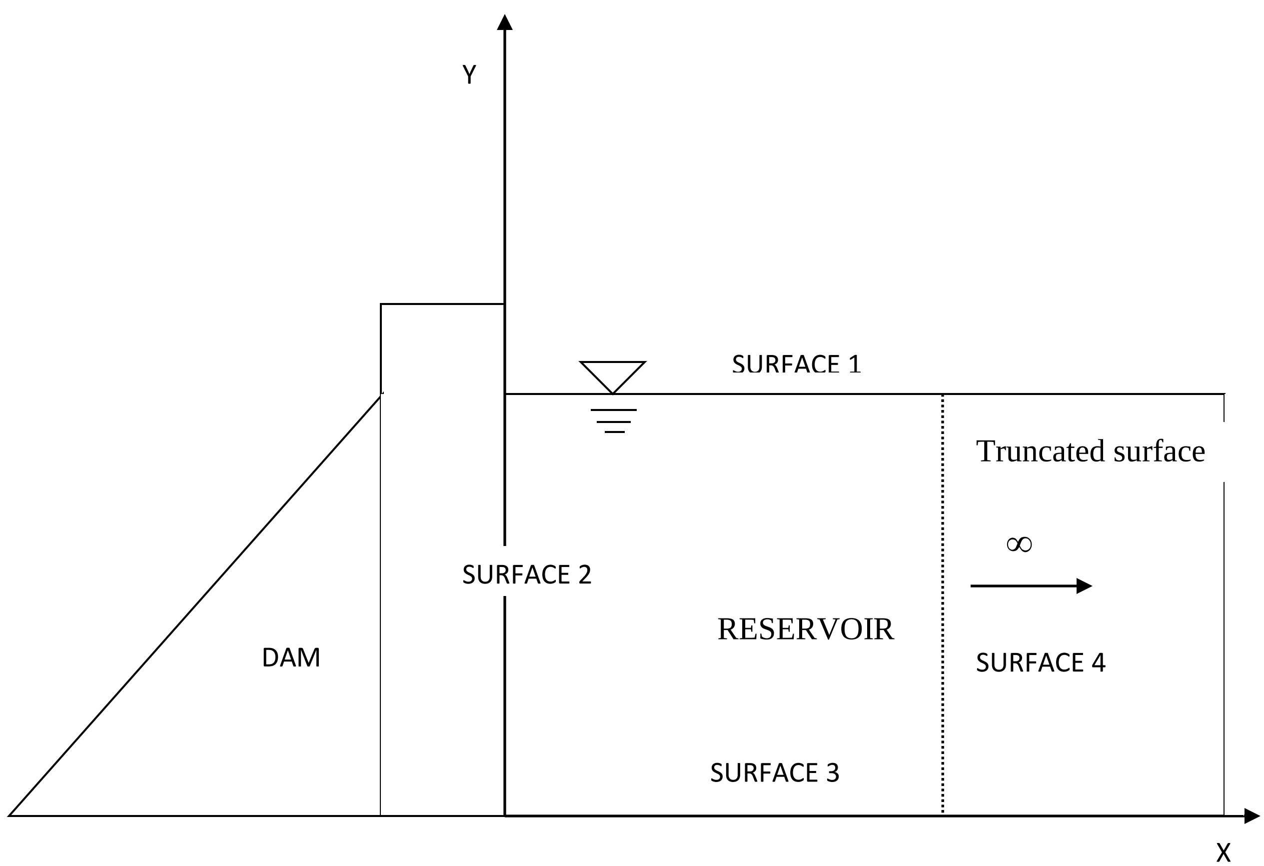

Figure 1 : Dam Reservoir System

The boundary condition of free surface (Surface I) considering the effect of surface wave is taken as follow:

$$\frac{1}{g}\ddot{p} + \frac{\partial p}{\partial y} = 0 \qquad (2a)$$

Boundary condition of free surface neglecting the effect if surface wave can be expressed as follow:

$$p\left(x, H_f\right) = 0 \qquad (2b)$$

Where, H_f is the depth of the reservoir.

The hydrodynamic pressure at dam-reservoir interface (Surface II) may be get from the following equation:

$$\frac{\partial p}{\partial n}(\,0, y, t) = -\rho_f a e^{i\omega t} \qquad (3)$$

Where $ae^{i\omega t}$ is the horizontal component of the ground acceleration, ω is the circular frequency of vibration and $i = \sqrt{-1}$, n is the outward directed normal to the elemental surface along the interface and $\rho_f$is the density of the fluid.

The hydrodynamic pressure at the bottom (Surface III) of the reservoir considering bottom absorption effect can be obtained from following equation:

$$\frac{\partial p}{\partial n}(x, 0, t) = -i\omega q\dot{p}(x, 0, t) \qquad (4)$$

Where the coefficient q is given as.

$$q = \frac{1}{c}\left(\frac{1-\propto}{1+\propto}\right) \qquad (5)$$

Here $\propto$ is frequency independent reflection coefficient.

The boundary condition at truncation surface (Surface IV) can be given as follows.

$$\frac{\partial p}{\partial n} = \left(\xi_m - \frac{1}{c}\right)\dot{p} \qquad (6)$$

According to Gogoi and Maity (2006), ξ_m can be obtain from the following equation.

$$\xi_m = -\frac{i\sum_{m=1}^{\infty}\frac{\lambda_m^2 I_m}{\beta_m}e^{-k_m x}(\Psi_m)}{\Omega\, c\sum_{m=1}^{\infty}\frac{\lambda_m^2 I_m}{\beta_m k_m}e^{-k_m x}(\Psi_m)} \qquad (7)$$

The value of χ is taken zero when the effect of gravity waves are neglected.

Assuming pressure as unknown variable and following Galerkin approach, the discretized form of Eq. (1) is given as below.

$$\int_\Omega N_{rj}\left[\nabla^2\sum N_{ri}p_i - \frac{1}{c^2}\sum N_{ri}\ddot{p}_i\right]d\Omega = 0 \qquad (8)$$

Where, *Ω* is the region under consideration, N_{rj} is the interpolation function for the reservoir. Using Green's theorem Eq. (15) may be written to as follows.

$$-\int_\Omega\left[\frac{\partial N_{rj}}{\partial x}\sum\frac{\partial N_{ri}}{\partial x}p_i + \frac{\partial N_{rj}}{\partial y}\sum\frac{\partial N_{ri}}{\partial y}p_i\right]d\Omega - \frac{1}{c^2}\int_\Omega N_{rj}\sum N_{ri}\,d\Omega\ddot{p}_i + \int_\Gamma N_{rj}\frac{\partial N_{rj}}{\partial n}d\Gamma p_i = 0 \qquad (9)$$

where *i* varies from 1 to total number of nodes and *Γ* represents the boundaries of the fluid domain. The last term of the above equation is given as follow.

$$\{F\} = \int_\Gamma N_{rj}\frac{\partial p}{\partial n}d\Gamma \qquad (10)$$

The whole system of equation may be written in a matrix form as follows.

$$[\overline{E}]\{\ddot{p}\} + [\overline{G}]\{p\} = \{F\} \qquad (11)$$

Where,

$$[\overline{E}] = \frac{1}{c^2}\sum\int_\Omega [N_r]^T[N_r]\,d\Omega \qquad (12)$$

$$[\overline{G}] = \sum\int_\Omega\left[\frac{\partial[N_r]^T}{\partial x}\frac{\partial[N_r]}{\partial x} + \frac{\partial[N_r]^T}{\partial y}\frac{\partial[N_r]}{\partial y}\right]d\Omega \qquad (13)$$

$$\{F\} = \sum\int_\Gamma [N_r]^T\frac{\partial p}{\partial n}d\Gamma = \{F_f\} + \{F_{fs}\} + \{F_{fb}\} + \{F_t\} \qquad (14)$$

Where subscripts *f*, *t*, f_s and f_b stand for free surface, truncation surface, fluid-surface interface and

Fluid-bed interface respectively.

For surface wave, $\{F_f\}$ can be written in finite element form as below.

$$\{F_f\} = -\frac{1}{g}[R_f]\{\ddot{p}\} \tag{15}$$

In which,

$$[R_f] = \sum \int_{\Gamma_f} [N_r]^T [N_r]\, d\Gamma \tag{16}$$

At the fluid-structure interface, where $\{a\}$ is the vector of nodal accelerations of generalized coordinates, $\{F_{fs}\}$ may be expressed as given below.

$$\{F_{fs}\} = -\rho_f [R_{fs}]\{a\} \tag{17}$$

In which,

$$[R_{fs}] = \sum \int_{\Gamma_{fs}} [N_r]^T [T][N_s]\, d\Gamma \tag{18}$$

Here, N_s is the shape function of dam structure and $[T]$ is the transformation matrix at fluid structure interface.

At the reservoir bed interface, $\{F_{fb}\}$ may be expressed as given below.

$$\{F_{fb}\} = i\omega q\, [R_{fb}]\{p\} \tag{19}$$

Where,

$$[R_{fb}] = \sum \int_{\Gamma_{fb}} [N_r]^T [N_r]\, d\Gamma \tag{20}$$

At the truncated surface $\{F_t\}$ may be expressed as given below.

$$\{F_t\} = \left(\xi_m - \frac{1}{c}\right)[R_t]\{p\} \tag{21}$$

Where,

$$[R_t] = \sum \int_{\Gamma_t} [N_r]^T [N_r]\, d\Gamma \tag{22}$$

Substitution of all term in Eq. (11) we get the following equation.

$$[\,E\,]\{\ddot{p}\} + [A]\{\dot{p}\} + [\,G\,]\{p\} = \{F_r\} \tag{23}$$

Where,

$$[E] = [\bar{E}] + \frac{1}{g}[R_f] \tag{24}$$

$$[A] = \frac{1}{c}[R_t] \tag{25}$$

$$[G] = [\bar{G}] + \xi_m[R_t] - i\omega q\,[R_{fb}] \tag{26}$$

$$\{F_r\} = -\rho_f[R_{fs}]\{a\} \tag{27}$$

Hydrodynamic pressure can be obtained by solving equation (23) using Newmark's integration method.

RESULTS AND DISSCUSSION

4.1 VALIDATION OF PROPOSED ALGORITHM

To determine hydrodynamic pressure distribution on the face of dam a MATLAB code is generated. For the purpose of validation of present algorithm, geometry and material properties of reservoir are considered as same as considered by Sami and Lotfi (2007). The depth of reservoir is considered as 116.19 m. The mass density of water is considered as 1000 kg/m^3. The acoustic velocity in water (c) is taken as 1440 m/s. The reservoir is truncated at a distance of 200.0 m. The result obtained from free vibration analysis is compared with the result of Sami and Lotfi (2007). First three natural frequencies are given below in Table 1.

Table 1 : Comparison of natural frequencies of the reservoir

Mode number	Natural Frequency(Hz)	
	Present study	Sami and Lotfi
1	3.1881	3.1151
2	4.882	4.7491
3	7.9293	7.7955

4.2 NUMERICAL RESULTS

Hydrodynamic pressure, developed in the unbounded reservoir, is obtained by solving the Eq. (23) using Newmark's integration method. Dam is considered as rigid. Height of reservoir is considered as 90 m and *L/H* ratio is taken as 0.5 and at the truncated face a nonreflecting boundary condition (Gogoi and Maity, 2006) is applied. Effect of surface wave is neglected. Reservoir bottom absorption is considered and the value of reflection coefficient is taken as 0.95. Unit weight of water is taken as 10 kN/m^3. The acoustic velocity in water (c) is taken as 1440 m/s. The reservoir geometry is discretized using eight node isoparametric element. Dynamic equilibrium equation is solved by Newmark's integration method and the analysis has been done by applying harmonic excitation. A convergence study has been done for finite element discretization and the results are presented in Table 2. N_h and N_v presents number of elements in horizontal and vertical direction respectively. From this convergence study N_h is taken as 5 and N_v is taken as 10.

Table 2 : Convergence test for meshing of dam and reservoir

N_h	N_v	Pressure Coefficient
5	8	0.726503
5	10	0.726505
5	12	0.726505

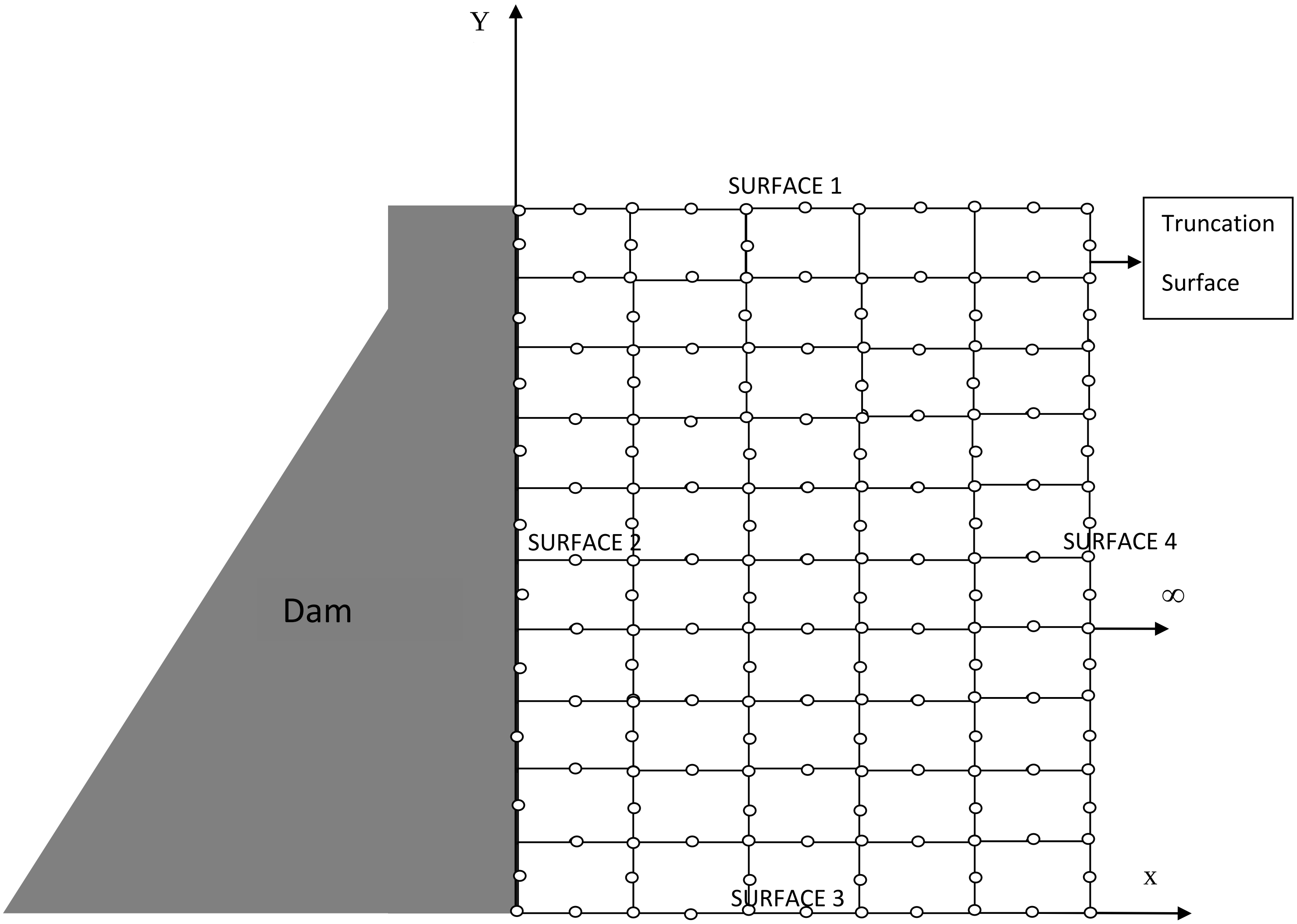

Figure 2 : Finite element mesh of Reservoir

In the first portion of the work hydrodynamic pressures at upstream face of dam are computed for different height of reservoir. Fluid is considered as incompressible and non-viscous in this study. The pressure at the depth of 45 m, 67.5 m and 90 m are determined by applying harmonic excitation. Each time *L/H* ratio is taken as 0.5 and at the truncated face a nonreflecting boundary condition (Gogoi and Maity, 2006) is applied. Effect of surface wave is neglected. Reservoir bottom absorption is considered and the value of reflection coefficient is taken as 0.95. Unit weight of water is taken as 10 kN/m^3. The acoustic velocity of water (*c*) is taken as 1440 m/s. Dynamic equilibrium equation is solved by

Newmark's integration method. The results are shown in Fig. 3. From these figure it is clear that hydrodynamic pressure at heel of dam increases with increase of height of reservoir and maximum hydrodynamic pressure is obtained for reservoir height as 90 m.

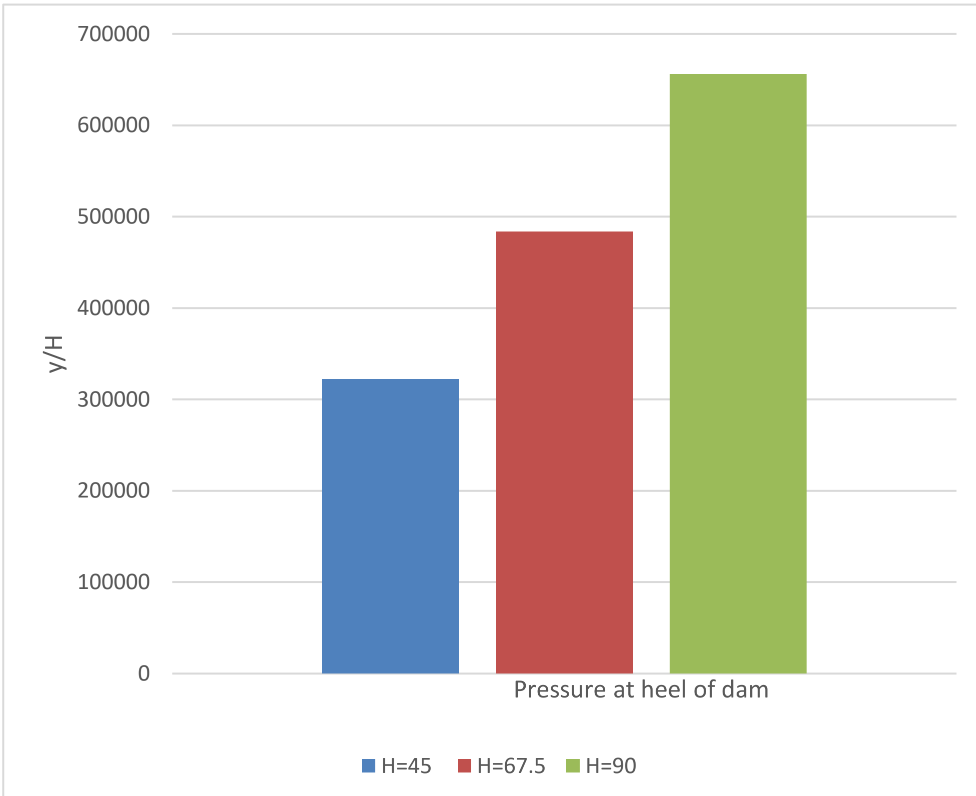

Figure 3 : Hydrodynamic pressure at heel of dam for different height of reservoir

Hydrodynamic pressure varies with change of inclination of face of dam. To determine the relation between the hydrodynamic pressure and the inclination of dam-reservoir interface height (*H*) of reservoir is considered as 90 m. *L/H* ratio is taken as 0.5. Value of reflection coefficient is taken as 0.95. Unit weight of water is taken as 10 kN/m^3. The acoustic velocity in water (*c*) is taken as 1440 m/s. Hydrodynamic pressure coefficient is determined for the inclination (θ) of face of dam as 70°, 80° and 90° respectively by applying harmonic excitation. Hydrodynamic pressure coefficient is the ratio of hydrodynamic pressure to maximum hydrostatic pressure.

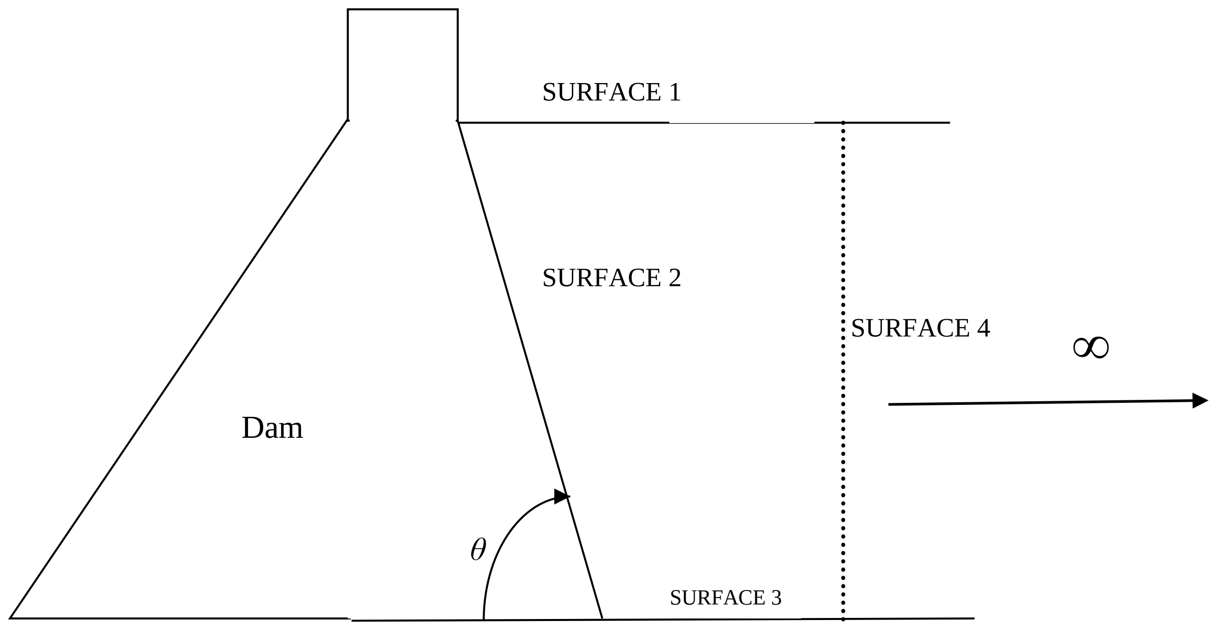

Figure 4 : A typical geometry of dam-reservoir system with inclined dam-reservoir interface

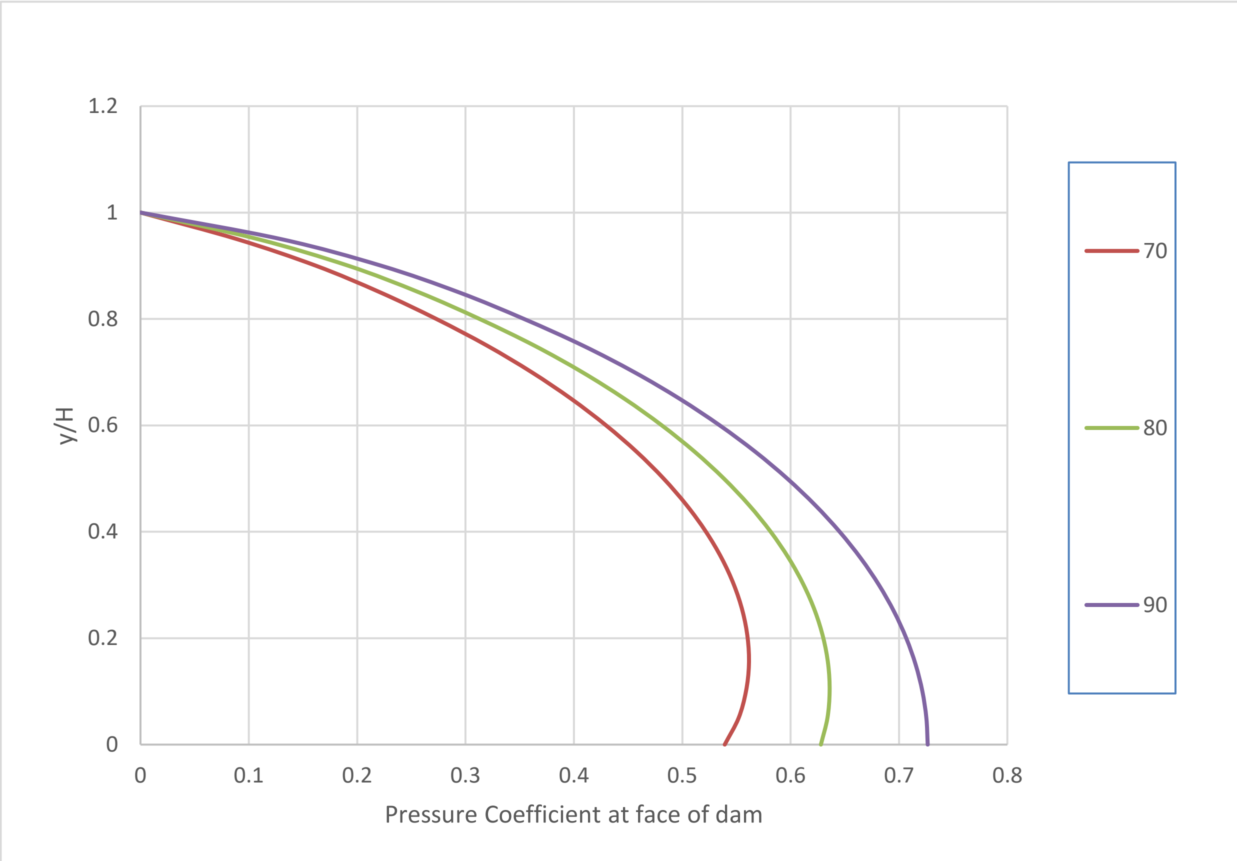

Figure 5 : Distribution of pressure coefficient at face of dam

Fig. 5 presents the distribution of pressure coefficient at face of dam for different inclination (θ) of dam-reservoir interface. From this figure we get that if the face angle of dam-reservoir increases then hydrodynamic pressure at heel of dam also increases. Fig. 6 presents the time history plot of hydrodynamic pressure coefficient at heel of dam for different value of face angle of dam. This figure illustrates that for increase of face angle of dam, hydrodynamic pressure at heel of dam increases.

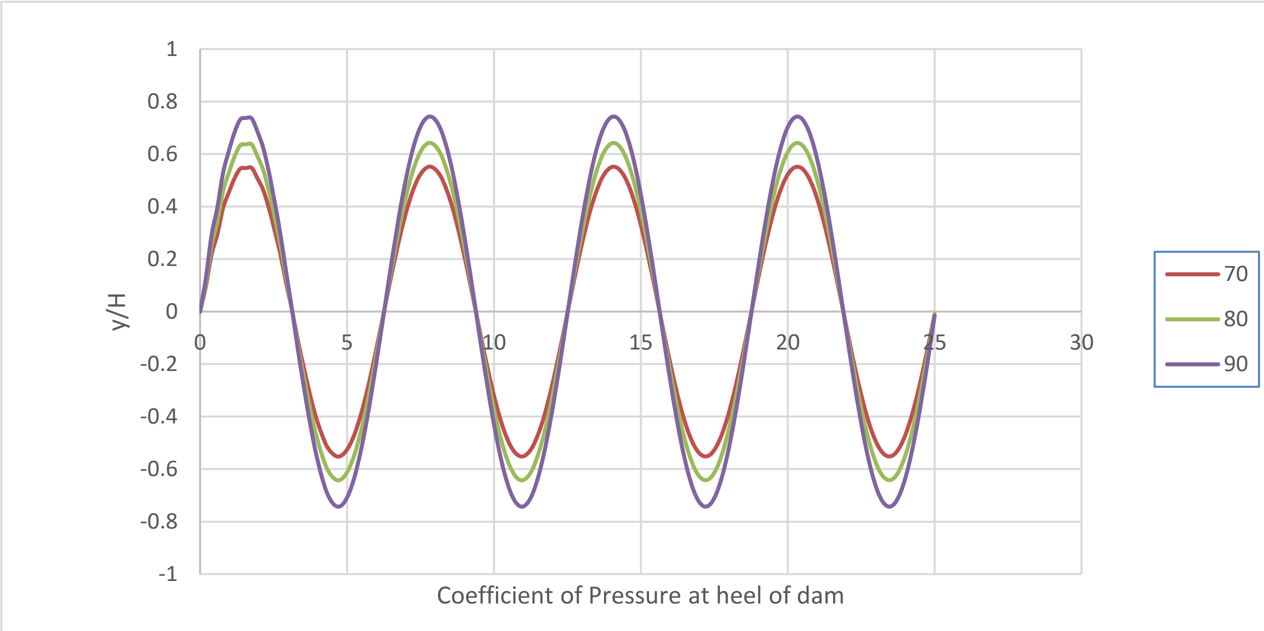

Figure 6 : Time history plot of hydrodynamic pressure coefficient at heel of dam.

To study the variation of hydrodynamic pressure with change of inclination of face of dam due to earth quake, again the analysis has been carried out for different face angle of dam. To determine the relation between the hydrodynamic pressure and the inclination of dam-reservoir interface height (H) of reservoir is considered as 90 m. L/H ratio is taken as 0.5. Value of reflection coefficient is taken as 0.95. Unit weight of water is taken as 10 kN/m^3. The acoustic velocity in water (c) is taken as 1440 m/s. Hydrodynamic pressure coefficient is determined for the inclination (θ) of face of dam as 70°, 80° and 90° respectively by applying Koyna earthquake (1967) excitation. The Horizontal accelerogram of Koyna earthquake is shown in Fig. 7.

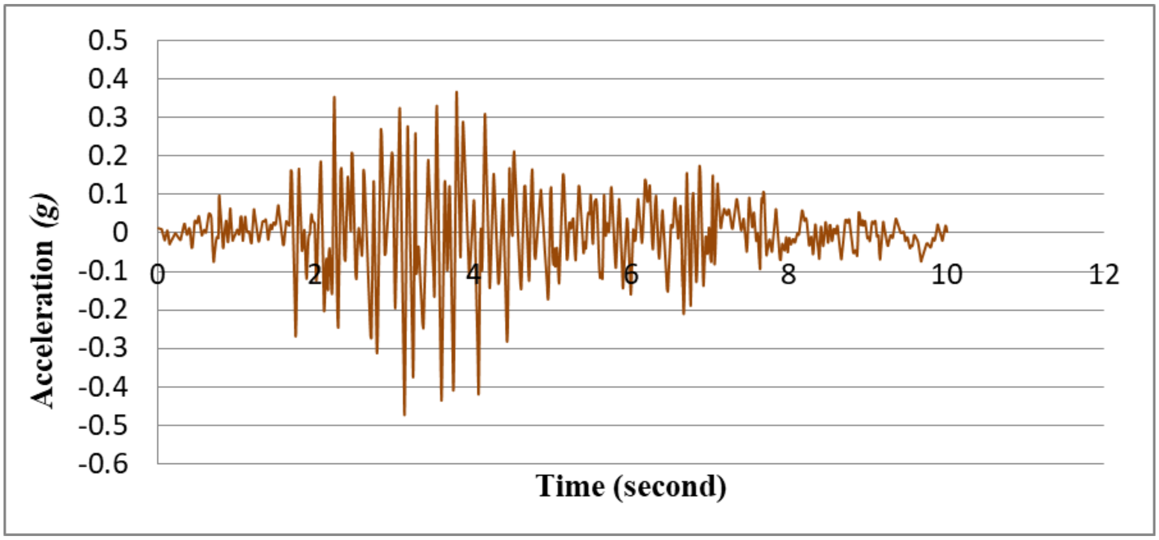

Figure 7 : Horizontal accelerogram of Koyna earthquake (1967)

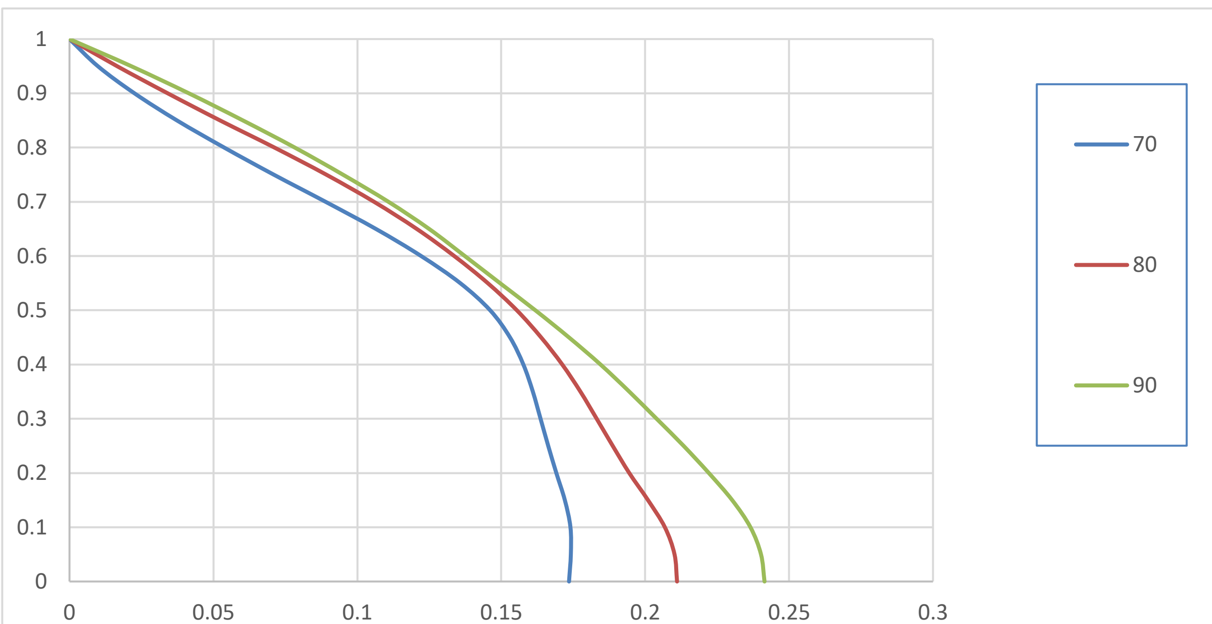

Figure 8 : Distribution of pressure coefficient at face of dam due to earthquake

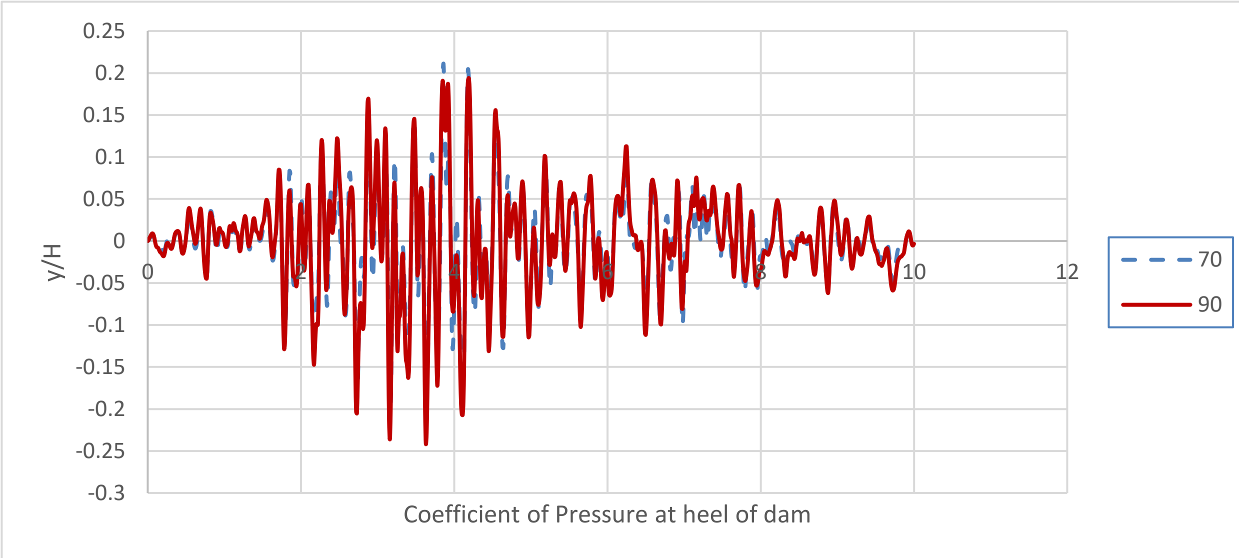

Figure 9 : Time history plot of hydrodynamic pressure coefficient at heel of dam due to earthquake

Fig. 8 presents the distribution of pressure coefficient at face of dam for different inclination (θ) of dam-reservoir interface due to earthquake excitation. From this figure we also get that if the face angle of dam-reservoir interface increases then hydrodynamic pressure at heel of dam also increases for earthquake. Fig. 9 presents the time history plot of hydrodynamic pressure coefficient at heel of dam due to earthquake excitation for different value of face angle of dam. This figure illustrates that for increase of face angle of dam, hydrodynamic pressure at heel of dam increases due to earthquake.

CONCLUSION

Hydrodynamic pressure is important for stability and safety of gravity dam. Height of reservoir, length of reservoir and inclination of dam reservoir interface influence the hydrodynamic pressure at face of dam. Present study is carried for determination of hydrodynamic pressure at face of dam for different height of reservoir and different inclination of dam reservoir interface for both harmonic and earthquake excitations. The salient features of the present work are given below.

- Hydrodynamic pressure at face of dam depends on height of the adjacent reservoir. Pressure at face of dam increases with increase in height of reservoir.
- Hydrodynamic Pressure distribution at the face of dam is approximately parabolic.
- Hydrodynamic pressure at heel of dam is maximum when the face of dam is vertical
- Maximum pressure occurs slightly above the heel when the face of dam is inclined.
- Hydrodynamic pressure at face of dam increases with increase in inclination of dam-reservoir interface.

SUGGESTION FOR FUTURE SCOPE

- More study is required on hydrodynamic pressure for different truncation length of reservoir.
- Study can be done for different value of absorption coefficient of reservoir bottom to understand the exact behavior of reservoir adjacent to gravity dam.
- Thorough study can be done for different truncation boundary condition to get more accurate result.
- Hydrodynamic pressure variation can be studied for different inclination of reservoir bottom.
- Dam-reservoir interaction can give more realistic idea about hydrodynamic pressure and as well as responses of dam structure.

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