

A simple lumped mass-damper idealization for dam-reservoir- foundation system for seismic analysis

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Abstract

A simple lumped mass-damper idealization of impounded reservoir water is suggested in this paper. The effect of impounded reservoir water was modeled as virtual lumped mass which simulates the hydrodynamic pressure according to Westergaard (1933), but the lumped mass approach does not consider the surface wave generation and wave transmission through the boundaries. On the other hand, acoustic/ water elements can be employed to model the dam-reservoir interaction which can capture the above mentioned effect, but that needs more computational effort and expertise. In this paper, equivalent dampers together with the virtual mass are lumped at the upstream face to simulate the effect of the impounded reservoir water on the dam. A simplified procedure is proposed for calculating the coefficient of dampers using the geometry of the reservoir and impedance of the foundation and dam materials. A comparison of response of lumped mass-damper model with acoustic water model is also presented.

Keywords: Lumped Damper approach; Dam-foundation-reservoir interaction; Concrete gravity dams; Compressible fluid element; Incompressible fluid; Absorbing boundary; Seismic analysis

Introduction

Concrete gravity dams are one of the most important civil engineering structures. Gravity dam stores a large amount of water in the reservoir, which contributes to the destabilizing forces on the dam. That is why, the modeling of the impounded reservoir water and its interaction with the dam and foundation attracts the attention of many researchers.

Reservoir considerably affects the earthquake response of the gravity dam. There are three ways to consider the reservoirs effect in the seismic response analysis of the dam system, for example, Westergaard, Lagrangian and Eulerian approaches. Westergaard approach considers the virtual lumped mass on the wet surface which stimulates the hydrodynamic effect on the upstream face of the dam [Westergaard, 1933; Zanger, 1953]. In Lagrangian Eulerian approach [Bayraktar *et al.*, 2011; Bleich and Sandler, 1970; Calayir *et al.*, 1996; Dunger, 1978; Kalateh and Attarnejad, 2011; Ross *et al.*, 2009; Zienkiewicz *et al.*, 1983] displacements are the variable in structure and pressures are the variable in the fluid. Special compatibility equation is required to establish the compatibility between the reservoir water and the dam-foundation system. In Lagrangian approach displacement is the variable for both impounded reservoir water and the dam-foundation system. No compatibility equation is required for Lagrangian approach [Hamdan, 1999; Wilson and Khalvati, 1983]. On the other hand, the performance of Westergaard model (incompressible water) and Acoustic water (compressible water) model were compared [Banerjee *et al.*, 2014]. It is observed that when the water is considered incompressible, the response is much higher as compared to when the water is considered compressible. To improve the results of Westergaard model, a simple lumped mass-damper model is proposed. A simplified lumped mass-damper model

From the results of dam response considering incompressible reservoir water and compressible water [Banerjee et al., 2014], it is clear that the lumped mass model (Westergaard model considering water as incompressible) gives almost 18-20% higher response than considering the reservoir water as compressible allowing for wave propagation and transmission of waves through the radiating boundary. Actually, p-waves propagated through the impounded reservoir water from the vibrating dam. As the ratio of energy transmission from one layer to another depends on the impedance (Z) of the layers, so the transmitted energy from the reservoir by different boundaries also depends on the shape of the reservoir and the impedance of the boundary. That is why, the wave propagation phenomena can be considered in the model by multiplying the impedance of water with the ratio of energy transmitted from the impounded water with the energy transmitting at the dam-reservoir interface.

Dam sections

Two high dams of different heights are designed using Optidam software [Banerjee *et al.*, 2015] are taken as examples. One is on the varying rock strata and another is on the single rock profile. The two dams are shown in Figure.1.

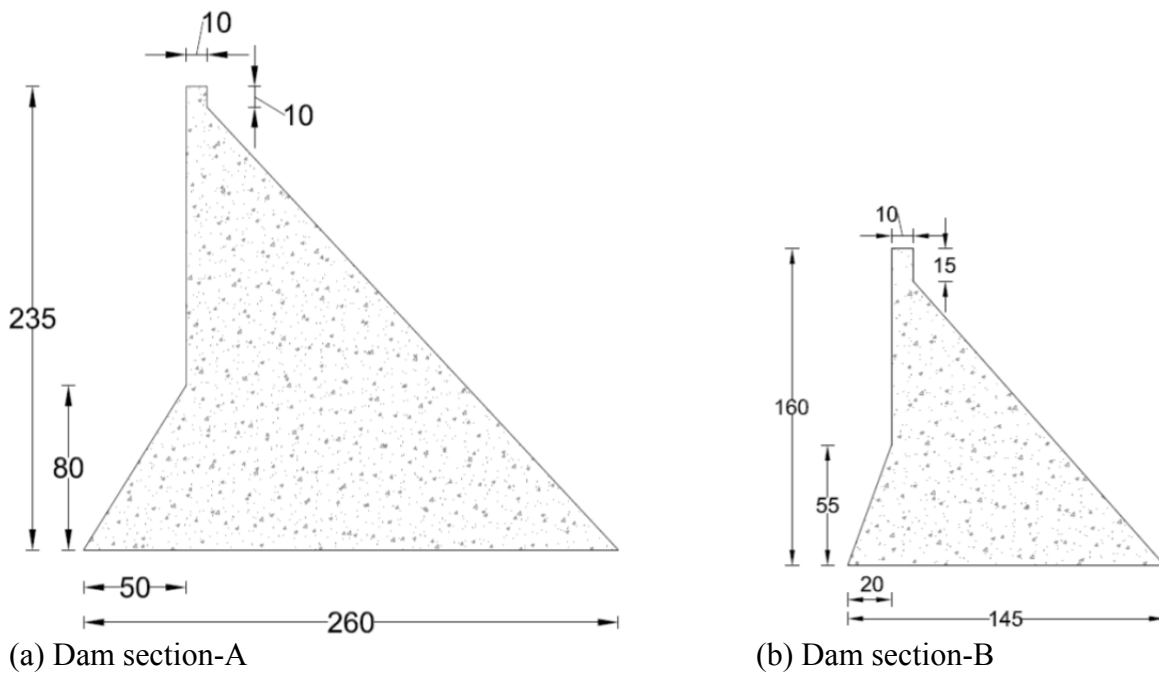


Figure.1 Two dam sections

The geometrical properties of the dams are given in Table-1.

Table-1 Geometric properties

	Height	Base width	Upstream slope	Downstream slope
Dam-A	235	260	1:0.625	1:0.9
Dam-B	160	145	1:0.360	1:0.8

The peak ground acceleration at the site is taken as 0.2g. The dam section –A is assumed to be on the layered rock strata. But the dam section-B is taken on single layer of rock. The property of concrete is given in Table-2.

Table-2 Property of Concrete

	Young Modulus (GPa)	Poisson Ratio	Density (kg/m ³)
Dam –A	30	0.15	2500
Dam –B	22	0.15	2400

The geotechnical data taken in the analysis is tabulated in Table.3.

Table-3 Geotechnical data

Dam Section	Rock layer	Depth (m)	Young Modulus (GPa)	Poisson Ratio	Density (kg/m ³)
Dam –A	Alluvium/Boulder	0-5	2	0.30	1800
	Fragmented Rock	5-20	7	0.32	2400
	Rock	20-250	10	0.32	2600
Dam –B	Rock	0-250	17	0.16	2000

There are two Philite strips of 10m width present at 60m and 160m from the upstream face of the dam. The two strips are parallel to each other making 22° with the horizontal. The property of philite strips is same as the fragmented rock layer for Dam-A. Bulk modulus and density of water is taken 2.07 GPa and 1000 kg/m³. Damping values of the different material are tabulated in Table-4.

Table.4 Damping Value (%)

Material	Concrete	Alluvium/Boulder	Intact Rock	Fragmented Rock
Dam-A	5	10	7	10
Dam-B	5	-	7	-

Computation of dampers coefficient

The energy loss from the non-reflecting boundary of the reservoir is not considered in Westergaard lumped mass model if the mass distribution is as per Eq(1).

$$\left(\begin{array}{l} C_w = \frac{C_m}{2} \left\{ \frac{y}{h} \left(2 - \frac{y}{h} \right) + \sqrt{\frac{y}{h} \left(2 - \frac{y}{h} \right)} \right\} \\ M_i = C_w \gamma_w h b (y_i - y_{i-1}) \end{array} \right) \quad (1)$$

To consider the energy loss, lumped dampers are attached at the upstream face of the dam along with the virtual mass due to incompressible water. The coefficient of the damper is calculated based on the energy transmission from different boundaries (except the dam-reservoir interface). Actually, the dampers are used to consider the ratio of energy going out from the radiation boundary and the energy impinging on the dam-reservoir interface. To compute the transmitted energy the following procedure as shown in Fig.2 is adopted.

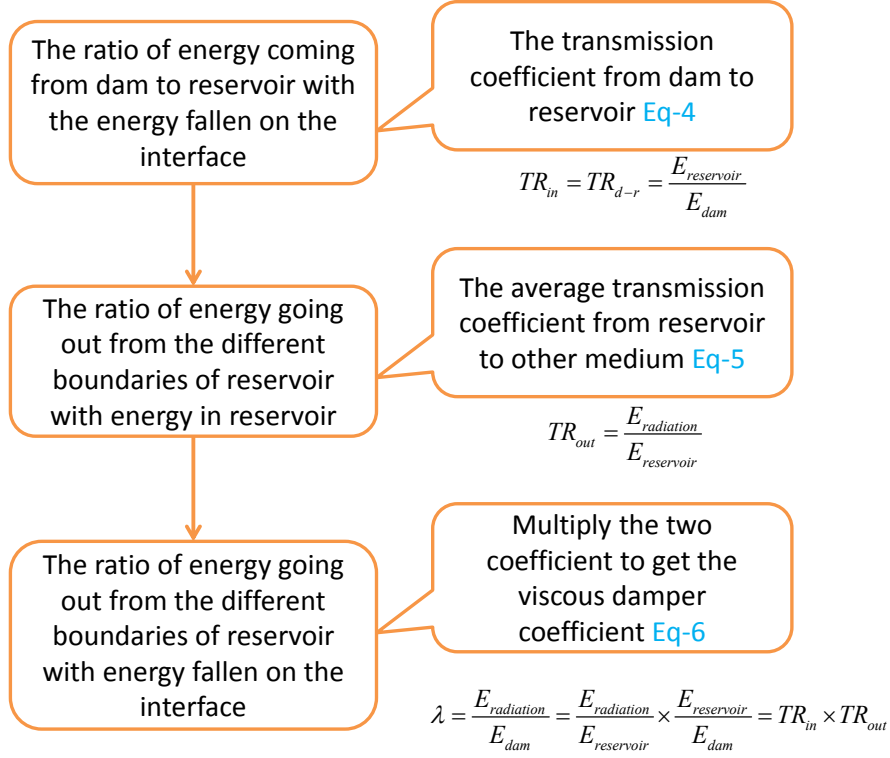


Figure.2 process to calculate the damping coefficient

The ratio of energy transmitted from one medium to the other is computed by

$$TR = 1 - \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \quad (2)$$

where, Z is the impedance of a medium depends on the p wave velocity (V_p) and the density (ρ) of the layer. Here s- wave velocity is not considered because s wave cannot propagate through the water.

$$Z = \rho V_p \quad (3)$$

The impedance of various layers are tabulated in Table-5 according to Eq (3) for two dams A & B.

Table-5 Impedance of different layers

Material	Dam-A			Dam-B		
	Density (ρ) (kg/m ³)	P wave velocity (V_p) (m/s)	Impedance (Z) (kg m ⁻² s ⁻¹) x10 ⁶	Density (ρ) (kg/m ³)	P wave velocity (V_p) (m/s)	Impedance (Z) (kg m ⁻² s ⁻¹) x10 ⁶
Concrete	2500	3500.0	8.75	2400	3133	7.52
Rock	2600	2342.3	6.09	2000	3010	6.02
Water	1000	1440.0	1.44	1000	1440	1.44

The ratio of total energy transmitted from dam to reservoir R_{d-r} and the total energy impinges on the interface (TR_{in}) should be equal, i.e.

$$TR_{in} = TR_{d-r} \quad (4)$$

The ratio of average energy transmitted out (TR_{out}) from the different boundaries of the reservoir is calculated as:

$$TR_{out} = \frac{\sum_{i=1}^n TR_i \cdot l_i}{\sum_{i=1}^n l_i} \quad (5)$$

So, the ratio of energy transmitted from different boundaries of the reservoir and the total energy impinges on the interface of the dam reservoir system (λ) is calculated by

$$\lambda = TR_{in} \cdot TR_{out} \quad (6)$$

The length and ratio of transmitted energy from different boundaries of reservoir are tabulated in Table.6.

Table-6. Properties of boundary

	Reservoir Boundaries	Z_1 (kg m ⁻² s ⁻¹) x10 ⁶	Z_2 (kg m ⁻² s ⁻¹) x10 ⁶	TR	length (m)	$TR \cdot l$
Dam-A	Free surface	1.44	0.00	0.00	550	0.0
	Infinite boundary	1.44	1.44	1.00	215	215.0
	Reservoir- Dam	1.44	8.75	0.48	230	110.4
	Reservoir- Foundation	1.44	6.09	0.61	512	312.3
Dam-B	Free surface	1.44	0.00	0.00	320	0.0
	Infinite boundary	1.44	1.44	1.00	140	140.0
	Reservoir- Dam	1.44	7.52	0.53	150	79.5
	Reservoir- Foundation	1.44	6.02	0.61	300	183.0

Where Z_1 and Z_2 are the impedances before and after a boundary. The co-efficient of virtual lumped damper at the upstream face is calculated by

$$C = \lambda c \rho_w A \quad (7)$$

where, C is the coefficient of a damper, c is the velocity of sound in water, ρ_w is the density of impounded reservoir water, and A is the tributary area of single damper. The evaluation of C is worked out in Table 7.

Table.7 Coefficient of dampers

Dam	TE _{in}	TE _{out}	λ	A (m ²)	C (N s m ⁻¹) x10 ⁶
Dam-A	0.48	0.42	0.20	75	21.60
Dam-B	0.53	0.44	0.23	75	24.84

Different dam models

The seismic response obtained by the proposed simplified method is compared with that of the compressible water model as well as incompressible water model. The three dam-reservoir models

are (i) with incompressible reservoir water (Westergaard lumped mass idealization, Fig. 3(a)), (ii) with compressible reservoir water (exact numerical model, Fig. 3(b)) and (iii) lumped mass-damper model (Fig.3(c)), are shown below. In the lumped mass-damper model, the virtual mass of the water is lumped on the wet surface in a similar fashion as if the reservoir water is treated incompressible and the energy used in surface waves and the radiation damping is replaced by equivalent dampers lumped on the wet surface.

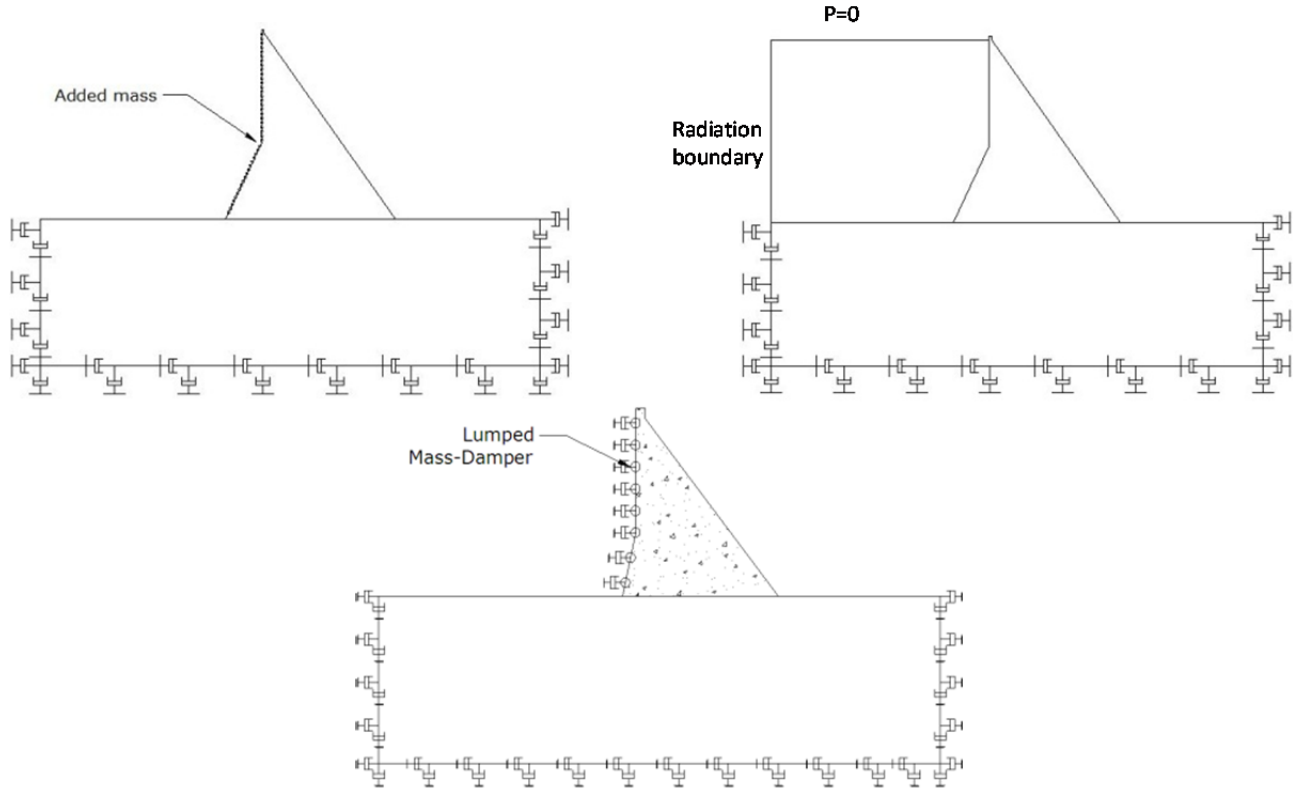
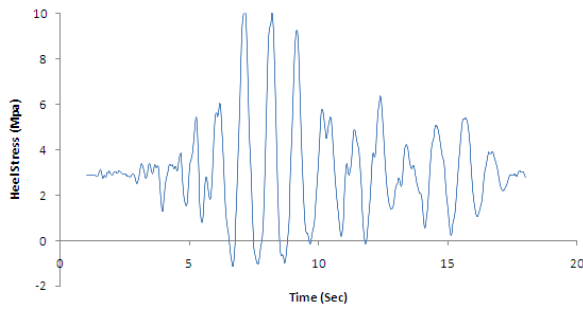


Figure-3 Different dam models

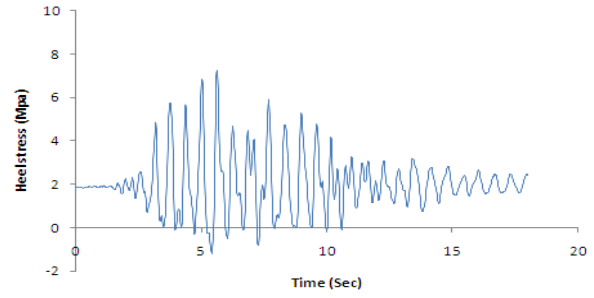
Response of dams

Baseline corrected deconvoluted accelerogram is applied at the base of the considered foundation. The stresses at the heel of the two dam models are plotted in Fig.4.

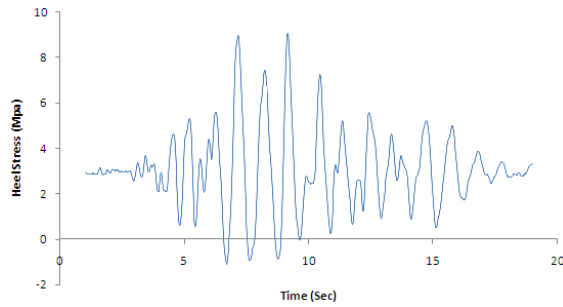
In Model-1, the incompressible water is replaced by virtual added mass on the wet surface where no radiation damping is considered at the truncated reservoir boundary. In Model-2 surface waves can be generated and the energy loss due to the outgoing waves at the truncated reservoir boundary attributes for lesser response when water is considered compressible. In Model-3 impounded reservoir water is replaced by lumped mass to consider the inertia of the water and lumped dampers to stimulate the energy dissipation from the reservoir. The principal stresses at the dam heel and u/s slope change for the Model-3 are comparable with Model-2.



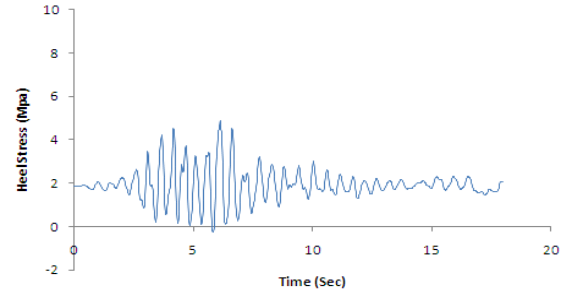
(a) Dam-A, Model-1 (Max 10.10 MPa)



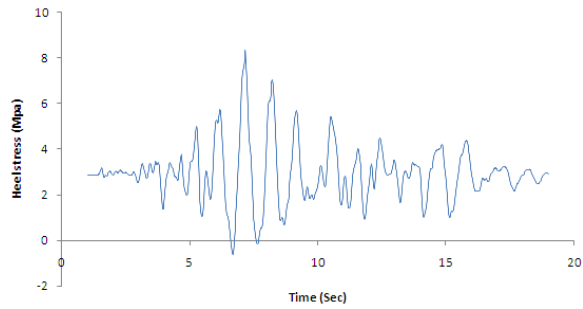
(b) Dam-B, Model-1 (Max 6.85MPa)



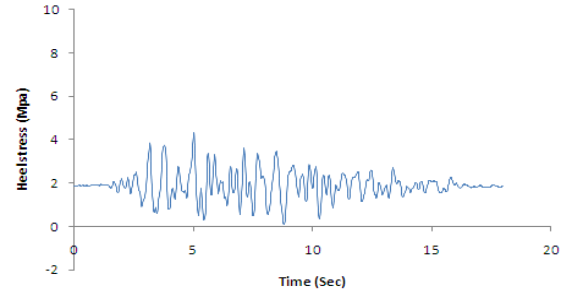
(b) Dam-A, Model-2 (Max 8.90MPa)



(d) Dam-B, Model-2 (Max 4.90MPa)



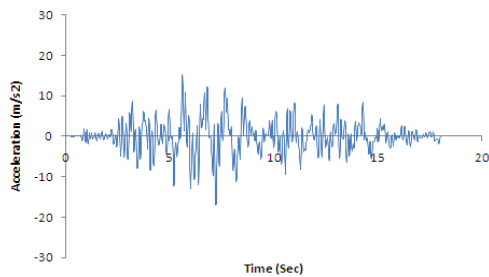
(e) Dam-A, Model-3 (Max 8.40MPa)



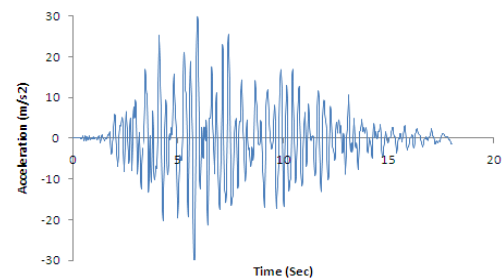
(f) Dam-B, Model-3 (Max 4.30MPa)

Figure-4 Principal stresses at heel

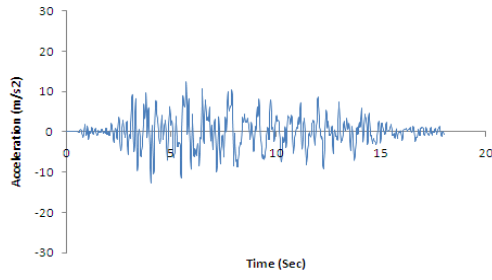
The maximum stresses at the heel and u/s slope change are reduced by 10-15% due to the fluid compressibility and energy dissipation through the boundaries. But the stress at the toe is not so much affected due to the compressibility of impounded water. Plot of dam crest acceleration for different models are plotted in Fig.5.



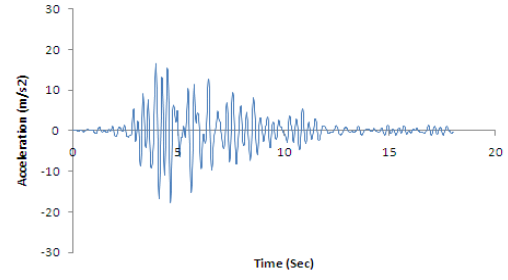
(a) Dam-A, Model-1 (Max acceleration 1.69g)



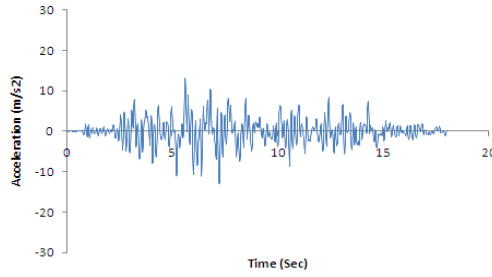
(b) Dam-B, Model-1 (Max acceleration 2.90g)



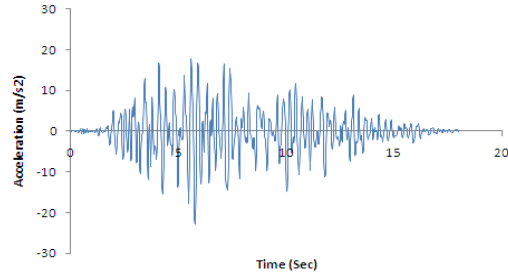
(c) Dam-A, Model-2 (Max acceleration 1.27g)



(d) Dam-B, Model-2 (Max acceleration 1.80g)



(e) Dam-A, Model-3 (Max acceleration 1.29g)



(f) Dam-B, Model-3 (Max acceleration 2.10g)

Figure.5 Crest acceleration for different cases

Crest acceleration for Model I is higher but it is almost same for the Model-2 and Model-3. The peak acceleration at different locations of the dam-foundation-reservoir system due to compressible and incompressible water models are tabulated in Table-8.

Table.8 Maximum acceleration and stresses at different locations of dam

Dam model	Model no.	Crest	Upstream slope		Heel	
		Acceleration (g)	Acceleration (g)	Stress (MPa)	Acceleration (g)	Stress (MPa)
Dam-A	Model-1	1.69	0.40	4.3	0.30	10.1
	Model-2	1.27	0.33	2.3	0.26	8.9
	Model-3	1.29	0.32	1.8	0.26	8.4
Dam-B	Model-1	2.90	0.70	4.0	0.43	6.8
	Model-2	1.75	0.28	2.0	0.24	4.9
	Model-3	1.80	0.30	1.9	0.28	4.3

Acceleration at crest, heel and upstream slope change location are reduced almost 18-24% due to the influence of compressibility of water. The virtual lumped mass model (Model I) gives result on a conservative side. The stress computed at the heel of the dam in Model-3 is slightly less than the stress calculated in Model-2 whereas acceleration and stresses at the u/s face are comparable with Model-2.

Conclusions

In this paper, an approach for approximation dam-reservoir system using a simplified lumped mass-damper model is suggested, where the energy loss due to radiation is modelled as lumped dampers on the upstream wet surface. Radiation damping due to outgoing waves is stimulated by lumping virtual dampers. The computation for the coefficient of lumped dampers depends on the density of water, sound wave velocity through water, tributary area of a single damper and the ratio of incoming energy and outgoing energy from the reservoir. The virtual lumped mass-damper

approach is applicable for both the layered media and homogeneous rock profile. The stresses and accelerations of the compressible water model and virtual lumped mass-damper model are comparable. The wave propagation is considered only in perpendicular to the boundary for the analysis. The simplified virtual lumped mass-damper model is found to be a good approximation for the response of dam reservoir foundation system for preliminary design of dam.

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