RESPONSE OF GRAVITY DAMS AGAINST STRONG EARTHQUAKE GROUND MOTIONS

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Abstract

Dams are extremely important lifelines of a country. They aid in the growth of the economy. The large-scale devastation due to an earthquake can generate irreversible losses. 2% of the dam failures all around the world take place due to earthquakes. Earthquakes not only cause immediate damage but are also capable of weakening the structure by decreasing its resistance against further damages. In this work, we study the effect of strong ground motion earthquakes on concrete gravity dams. The strong ground motions lying within shallow depths are felt powerfully by the dams, since the high frequency waves are not filtered. This causes more damage to the dam as there is a high probability of resonance in higher modes, a result of the high frequency content in the ground motion. 5 strong ground motions in the Indian Subcontinent have been selected and applied on the Koyna dam which was constructed in the year 1963.
2D analysis of the dam has been performed in standard software. Qualitative analysis of dams shows that there are 3 regions which are most susceptible to damage within a dam cross-section i.e., neck, body and the heel of the dam.

In this paper, the displacement of crest and the formation of tensile stresses at the 3 zones - neck, body, heel of the dam due to these 5 strong ground motions is analyzed. The point of highest tensile stress is most susceptible to damage and failure in the face of an earthquake. When the structure is exposed to the ground motions, under normalized peak ground accelerations (PGAs), the structure behaves differently based on the effect of the frequency content of the input signal. By Normalizing the PGA of the ground motion, we grasp an idea of the effect of frequency content on the dam structure.

Keywords: Gravity dam; Stress analysis; Qualitative failure analysis; Frequency Content; Deterministic Analysis

1. Introduction

Concrete gravity dams are important lifeline structures of a country. Hence, the risk associated to the dam is large and entails economic and human loss. The Koyna dam, situated in Maharashtra, India, has been analyzed in this paper. The Koyna earthquake occurred on December 11th,1967 near Koyna dam causing damage to the dam cross-section. The damage occured as formation of horizontal cracks along the cross-section of the dam monolith body. In 1973, Anil K. Chopra and P. Chakrabarti examined the response of the dam to strong ground motion recorded during Koyna earthquake by FEM analysis and anticipated the cracking on the monoliths based on stress results.They found large tensile stresses formed in the dam body. Hence, linear models for analysis of the dam fall short in explaining the amount of damage and stability of the dam. A nonlinear dynamic analysis should be adopted for analysis in order to obtain the realistic behavior of concrete dams. Many non-linear analyses have been carried out on the dam to analyze its response to earthquake ground motions. Calayir and Karaton (2005) performed a seismic analysis on the Koyna dam using the records of Koyna earthquake with modeling dam-reservoir interactions and a rigid foundation. They used this analysis to study the effect of cracking on the response of this concrete gravity dam. Their results showed that appearance of cracks in the neck of this dam is due to a change in the slope of this section (Calayir and Karaton, 2005).
Many researchers investigated the effects of near-fault and far-fault ground motions on structural behaviors e.g (Durucan and Dicleli, 2015; Ruiz-Garcia, 2011; Wu et al., 2017). Zhang and Wang (2013)[1] investigated these effects on the Koyna concrete gravity dam by assuming non-linear behavior of concrete material and comparing the results of local and global damage indices for the dam body under near and far fault ground motions. In this paper we intend to study the effect of both frequecy and amplitude on the damage of the dam.

For this, 7 ground motion parameters (GMPs) have been selected and 3 engineering demand parameters (EDPs) have been selected. These quantitative measures have been compared to analyse the relation between strong ground motions and damage to dam body (when subjected to the strong ground motion).

2. Numerical modelling of dam

The highest non-overflowing monolith of the Koyna dam is modelled. The monolith is 103 m high and 71 m wide at its base. Fig.1a) illustrates the dam cross-section. The depth of the reservoir is 91.75 m. Finite element mesh is generated assuming plane stress conditions as shown in Fig. 1b). Material properties of concrete are given in Table 1. The dam is initially subjected to gravity loading due to self-weight and hydrostatic pressure. Dam–foundation interactions are neglected by assuming that the foundation is rigid. The dam–reservoir dynamic interactions resulting from the ground motion is modelled using the Westergaard added mass technique. According to Westergaard (1933), the hydrodynamic pressures that the water exerts on the dam during an earthquake are the same as if a certain body of water moves back and forth with the dam while the remainder of the reservoir is left inactive. The added mass per unit area of the upstream wall is given in approximate form by the expression , $\frac{7}{8}\rho_w\left(h_w(h_w-y)\right)^{1/2}$, with $y \leq h_w$, where ρ_w is the water density and y is the height along wall.

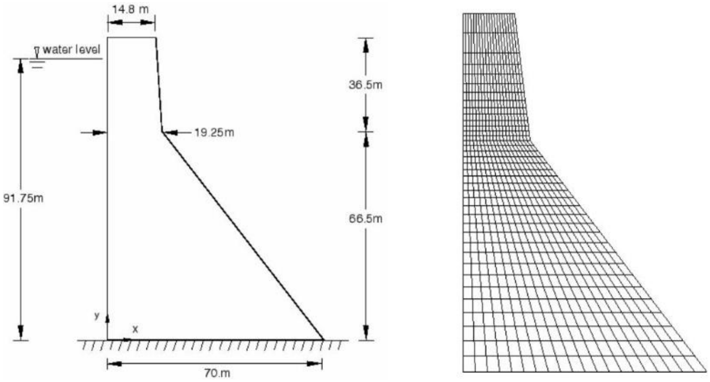


Fig. 1 a) Koyna Dam Cross-section b) Finite Element Mesh of dam cross-section

The dam has been modelled using ABAQUS [2]. The mechanical property of concrete has been modelled using the Concrete Damaged Plasticity (CDP) model proposed by Lubliner et al (1989) and Lee and Fenves (1998), to understand the nonlinear behavior. The parameter values of the model are taken from (Zhang et al., 2013) [1]. The damage dissipation energy is calculated by considering the Rayleigh damping with 5% damping ratio.

Table 1 – Material Properties of Concrete

Material Property	**Value**	**Material Property**	**Value**
Young's modulus	31027 Mpa	Compressive initial yield stress	13.0 Mpa
Poisson's ratio	0.15	Compressive ultimate stress	24.1 Mpa
Density	2643 kg/m^3	Tensile failure stress	2.9 Mpa

3. Ground Motions Parameters

5 strong ground motions have been selected and applied to the dam cross-section. The acceleration in horizontal direction versus time plots have been plotted below.

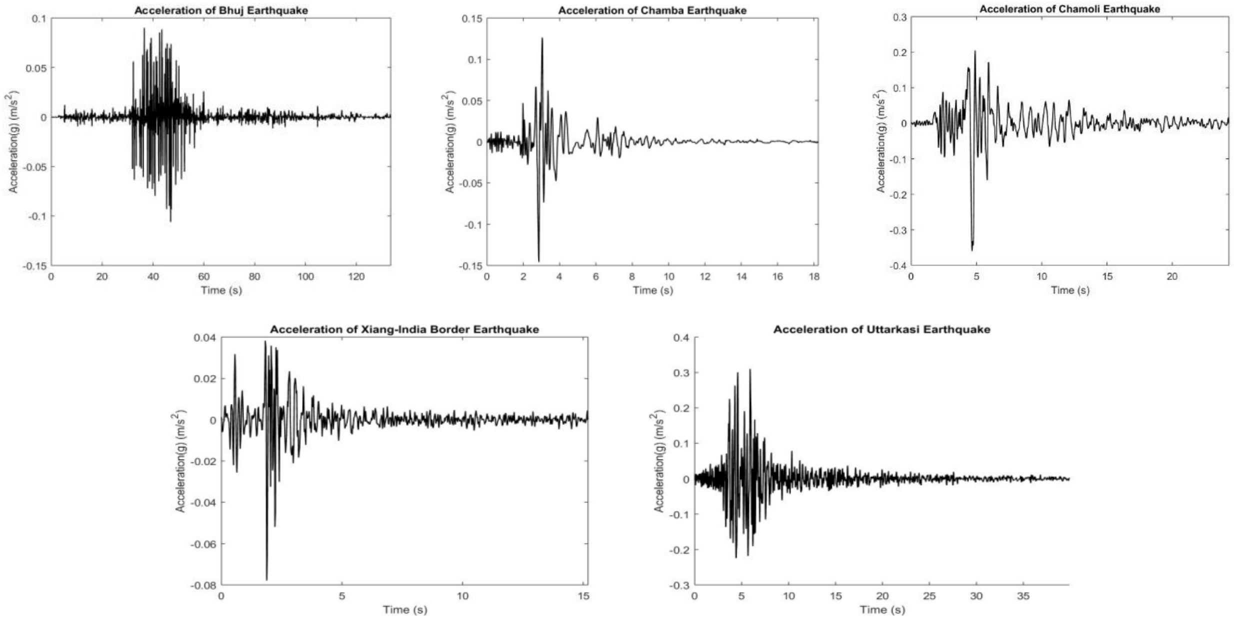


Fig.2 – Ground motion acceleration(g) in m/s^2 of (clockwise from left top corner) a) Bhuj , b) Chamba, c) Chamoli , d) Xiang-India border, e) Uttarkasi Earthquakes.

3.1 Ground motion parameters considered

Ground motion parameters (GMP) quantitatively represent a ground motion time history. A ground motion time history constitutes of 3 characteristics : Amplitude, frequency and duration. Amplitude is considered as the governing phenomenon for damage potential of the seismic wave, while frequency and duration are said to affect the amplitude. However, normalized amplitudes show varying damage potentials based on frequency thus establishing that frequency is not only indirectly affecting the damage potential (through the amplitude) but is capable of direct damage to the structure as well. Few ground motion parameters used in this paper are tabulated in Table 2 [3].

Table 2 – Description of Ground Motion Parameters

S. no	GMP	Description
1	Peak ground acceleration(PGA)	Peak maximum absolute value of acceleration time history
2	Peak ground velocity (PGV)	Peak maximum absolute value of velocity time history
3	Predominant frequency (F_p)	Frequency corresponding to maximum value of Fourier amplitude spectrum (Kramer 1996)
4	Significant duration (T_{sig})	$T_{sig} = T_{(5-95\%)}([a(t)]^2)dt$ is the duration between 5 and 95% thresholds of the energy plot (Trifunac and Brady 1975)

5	Arias Intensity (I_a)	$I_a = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2\,dt$ Energy of the acceleration time history (Arias 1970). I_a linearly varies with change in PGA.
6	Damage Factor (I_d)	$I_d = \frac{2g}{\pi} \times \frac{I_a}{(PGA.PVA)}$ Related to the number of plastic cycles and therefore the energy content of the earthquakes. (Consenza and Manfredi, 2002)

Table 3 – GMPs of selected Earthquake Ground Motions

Earthquake	PGA (g) m/s^2	PGV m/s	F_p m/s^2	T_{sig} s	I_a m/s	I_d	PGV/PGA s
Bhuj	0.11	45.13	0.3006	67.86	1.0988	1.4342	425.7293
Chamba	0.15	7.65	2.9449	3.72	0.0686	0.3839	52.4847
Chamoli	0.36	45.85	1.6678	8.88	0.7994	0.3026	127.4309
Xiang-India Border	0.08	1.94	3.9841	4.28	0.0147	0.6077	24.8658
Uttarkasi	0.31	18.51	2.9099	6.84	0.9635	1.0490	59.7330

Table 4 – GMPs of selected Earthquake Ground Motions (Normalized)

Earthquake	PGA (g) m/s^2	PGV m/s	F_p m/s^2	T_{sig} s	I_a m/s	I_d	PGV/PGA s
Bhuj	0.1	42.5729	0.3006	67.86	0.9777	1.4342	425.7293
Chamba	0.1	5.2485	2.9449	3.72	0.0323	0.3839	52.4847
Chamoli	0.1	12.7431	1.6678	8.88	0.0617	0.3026	127.4309
Xiang-India Border	0.1	2.4866	3.9841	4.28	0.0242	0.6077	24.8658
Uttarkasi	0.1	5.9733	2.9099	6.84	0.1003	1.0490	59.7330

PGA independent GMPs: T_{sig} ,I_d , F_p and PGV/PGA remain constant through changing PGAs. These parameters aid in understanding the response of the dam to the varying PGAs of a given ground motion.

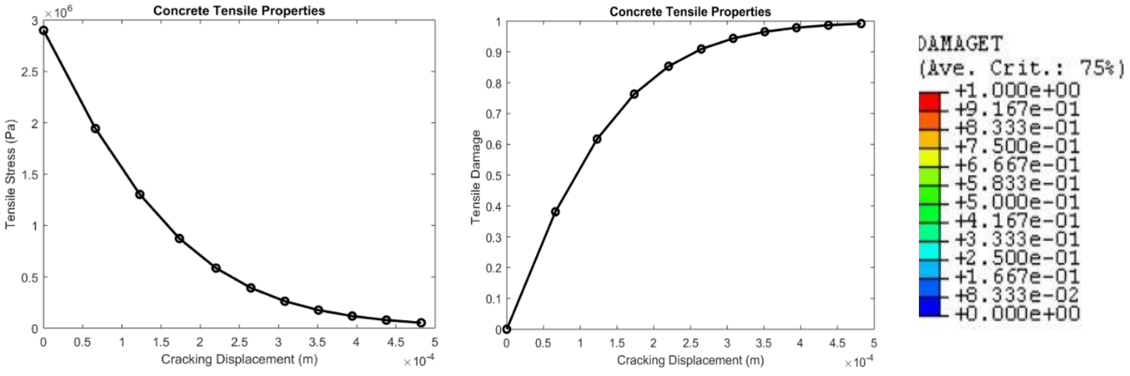
PGA dependent GMPs: The amplitude dependent GMPs (PGA, PGV, I_a) help us directly correlate the damage to the dam to the changing PGA.

5. Engineering Demand parameters

Engineering Demand Parameters (EDPs) are structural response quantities that can be used to predict damage to systems. 3 engineering demand parameters have been used to study the response of the dam to the earthquake ground motion.

a) Maximum crest displacement (in meters)

b) Tensile damage to dam body: High tensile forces are developed in the dam body leading to tensile failure of the structure. Relationship between Tensile stress and Cracking displacement, and Tensile damage and Cracking displacement is shown in Fig. a) and Fig. b).



a) b) c)

Fig. 3 a) Tension Stiffening b) Tension Damage and c) its representation in ABAQUS

c) Damage Dissipated Energy: If damage occurs in the material, not all the applied elastic strain energy is recoverable. At any given time, the stress, σ^c, can be expressed in terms of the "undamaged" stress, σ^u , and the continuum damage parameter, d as $\sigma^c = (1-d)\sigma^u$.
The damage parameter, d, starts at zero (undamaged material) and increases to a maximum value of no more than one (fully damaged material). Hence, applied elastic strain energy can be written as,

$$E_S = \int_0^t \left(\int (1-d)\sigma^u : \varepsilon^{el} dV \right) d\tau$$

We assume that, upon unloading, the damage parameter remains fixed at the value attained at time t. Therefore, the recoverable strain energy is equal to

$$E_E = \int_0^t \left(\int (1-d_t)\sigma^u : \varepsilon^{el} dV \right) d\tau$$

and the energy dissipated through damage is equal to $E_S - E_E$.

$$E_D = \int_0^t \left(\int (d_t - d)\sigma^u : \varepsilon^{el} dV \right) d\tau$$

where ε^{el} is elastic strain tensor.

6. Damage in Dam

When subjected to strong ground motions, gravity dams may be damaged in different modes. Damage can be categorised into 5 levels [4].

1. **Level I Complete dam**: The dam is complete, with only local microcracks which don't influence normal functioning of the dam.
2. **Level II Slight damage**: Localized macrocracks occur, with length shorter than one third of the cracking path, and the dam can restore normal function with minor repair in a short time.
3. **Level III Medium damage**: More cracks over the dam body occur, with length longer than one third of the cracking path, yet the dam is not broken and can restore normal function with major repair.
4. **Level IV Severe damage**: Cracks penetrates through the dam, dam head gets broken off, recovery is almost impossible.
5. **Level V Collapse of dam**: Dam is broken off at lower half of the dam body, water pounding function is totally lost, recovery is impossible.

7. Results and Discussion

7.1 Tensile damage and maximum crest displacement

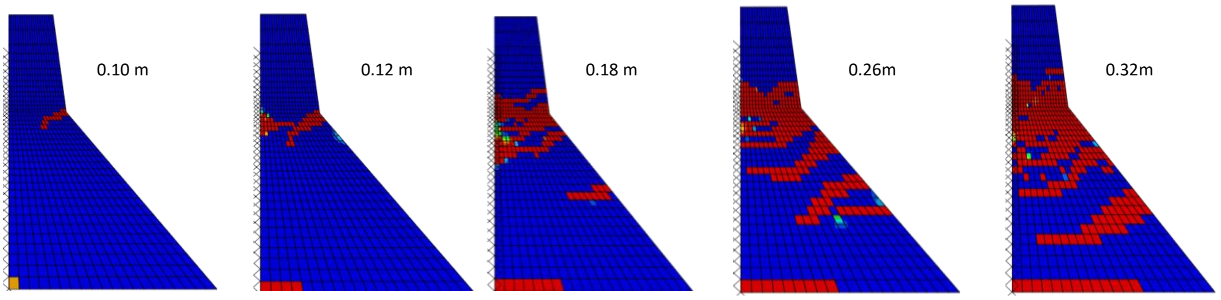


Fig. 4 a) Uttarkasi Earthquake response $F_p = 2.9009$ Hz

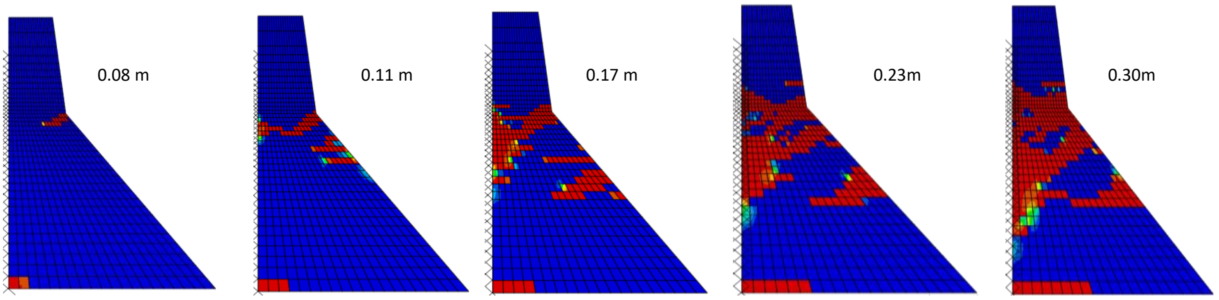


Fig. 4 b) Chamba Earthquake response $F_p = 2.9449$ Hz

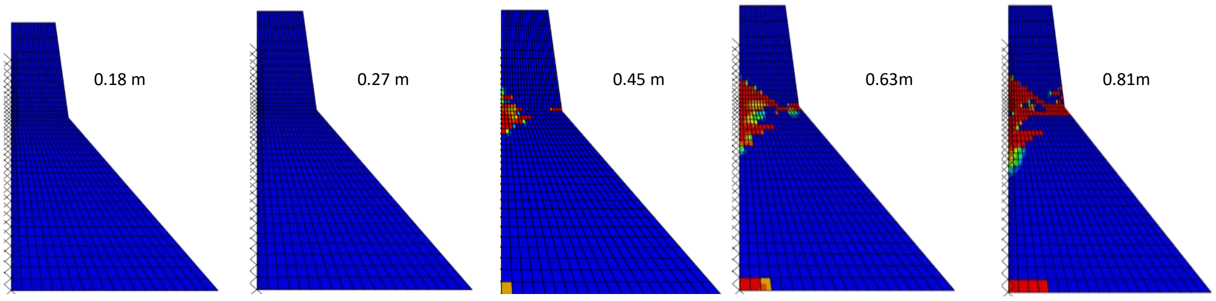


Fig. 4 c) Xiang-India Earthquake Response, $F_p = 3.9841$ Hz

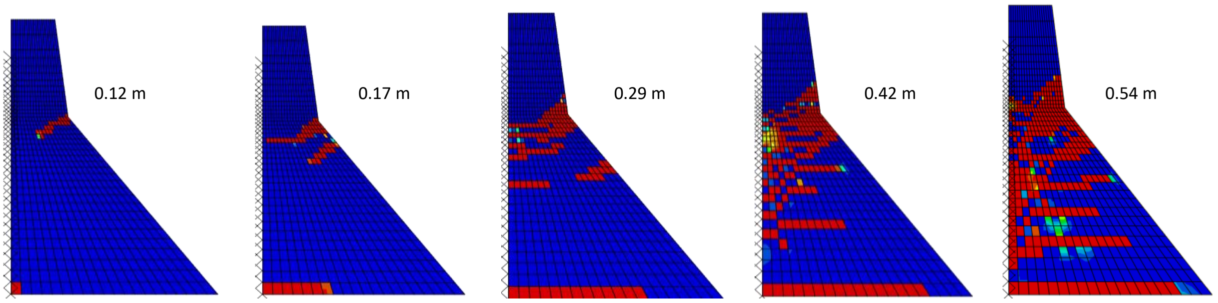


Fig. 4 d) Chamoli Earthquake Response, $F_p = 1.6678$ Hz

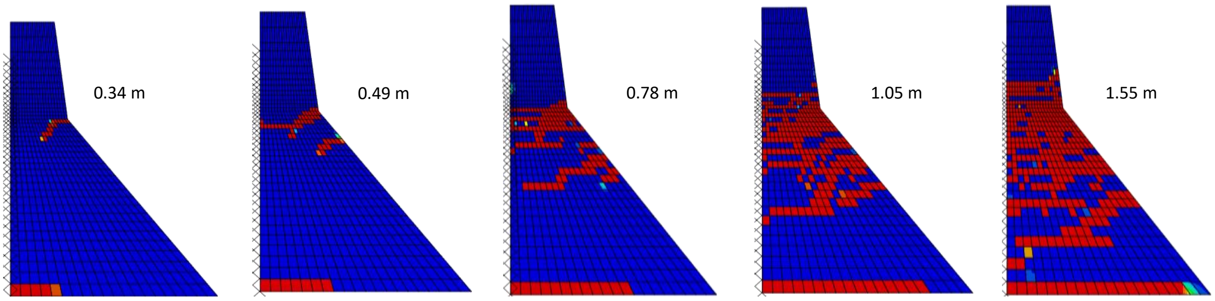


Fig. 4 e) Bhuj Earthquake Response, F_p = 0.3006 Hz

Cracks first appear near the heel, then proceed to the neck and then appear near the body. Based on Fig. 4 we can say that for a ground motions, as the **PGA increases**, tensile damage occurs at a higher intensity along the same crack path. The zone of cracking remains the same. With increase in **PGA** the **crest displacement** increases. Across ground motions, as the **peak Fourier frequency (F_p)** of ground motion increases, the crest displacement decreases (with an exception of Xiang-India Border earthquake). The variation of Maximum crest displacement along PGA and F_p is plotted in Fig. 5 (a) and (b).

Percentage Area of dam body under tensile damage (%D_t) increases as **PGA** increases. **%D_t** decreases with increase in **F_p.**

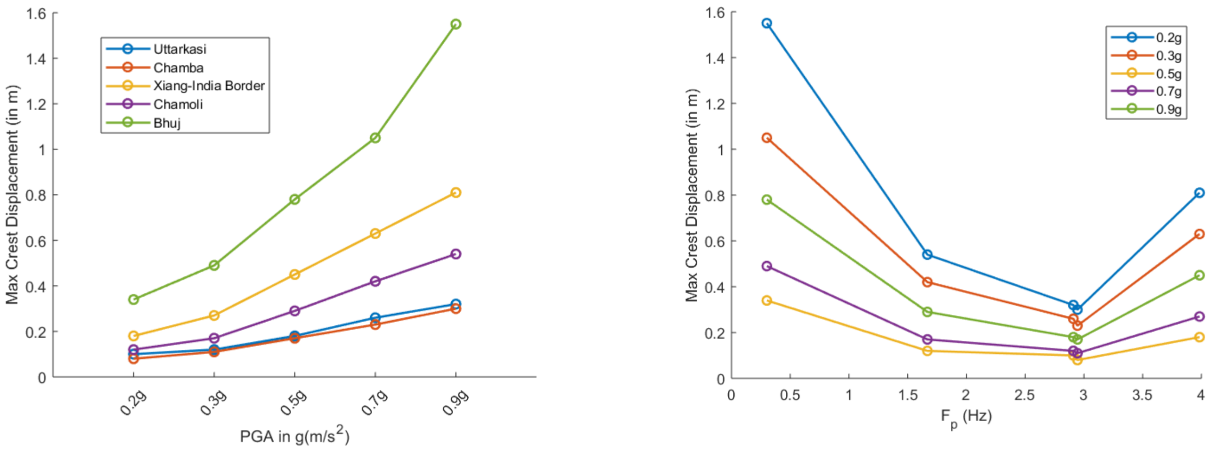


Fig. 5 – Maximum Crest displacement versus a) PGA and b) F_p for the 5 ground motions.

Fig. 4 a) to e) show the cracked profile of the dam cross-section. Based on Fig. 4 and the Damage levels discussed in Section 6, the Damage levels for the 5 earthquakes with varying PGA has been tabulated below.

EQ/PGA	0.2g	0.3g	0.5g	0.7g	0.9g
Uttarkasi	Level 2	Level 3	Level 4	Level 5	Level 5
Chamba	Level 2	Level 3	Level 4	Level 5	Level 5
Xiang-India	Level 1	Level 1	Level 2	Level 4	Level 4
Chamoli	Level 3	Level 3	Level 4	Level 5	Level 5

Bhuj	Level 3	Level 3	Level 4	Level 5	Level 5

Koyna dam is most vulnerable near the neck of the dam. Since the water level is higher that the neck , cracking of the neck leads to flooding, causing large scale loss and devastation. Hence for PGAs greater than 0.3g, dam is severely damaged.

7.2 Damage Dissipated Energy

The damage dissipated energy for a ground motion scaled to multiple PGA is shown below.

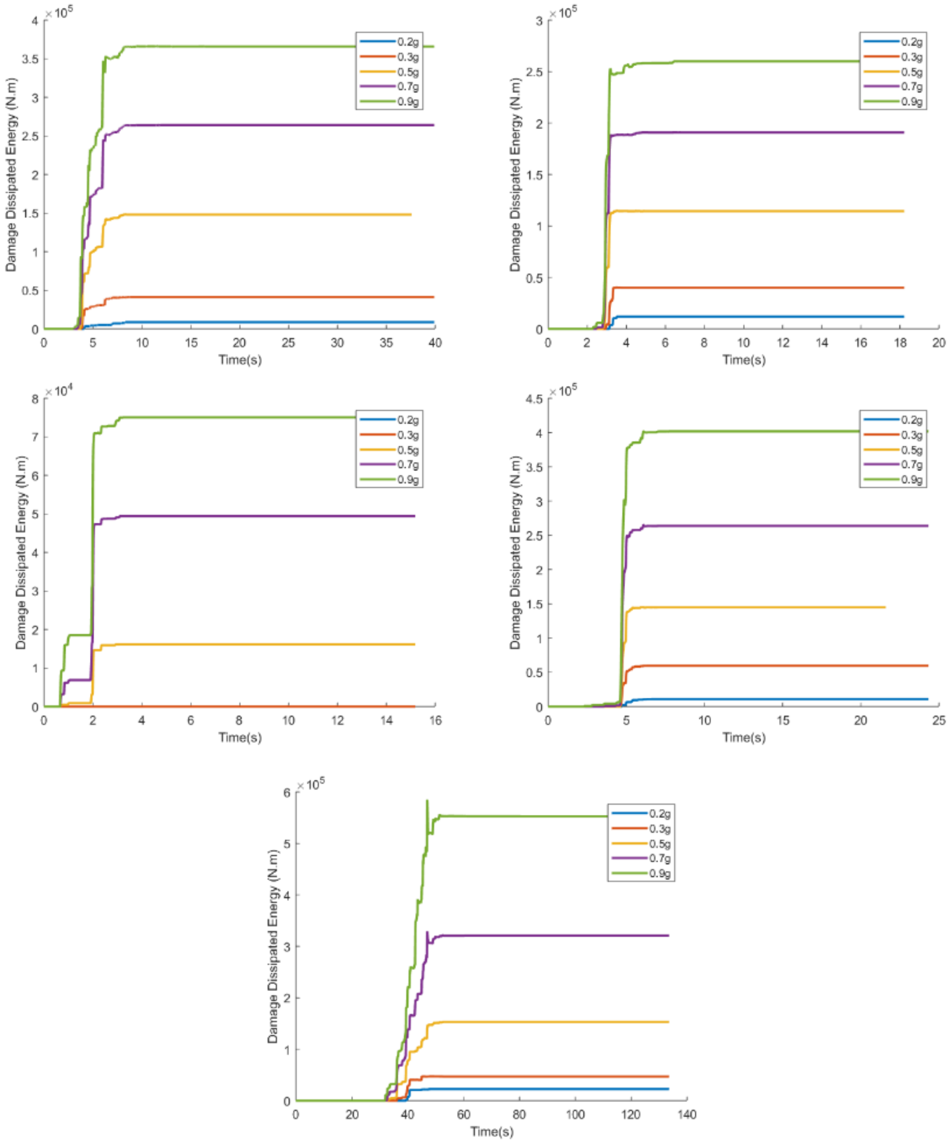


Fig. 6 – Damage dissipation energy of ground motions (from top left corner)
a) Uttarkasi b) Chamba c) Xiang-India Border d) Chamoli e) Bhuj

7.3 Damage Dissipated Energy and Arias Intensity

Fig. 5 shows the relation between Arias intensity and Damage dissipated energy (DDE). DDE has been normalized to 1, for all PGA, for a given earthquake.

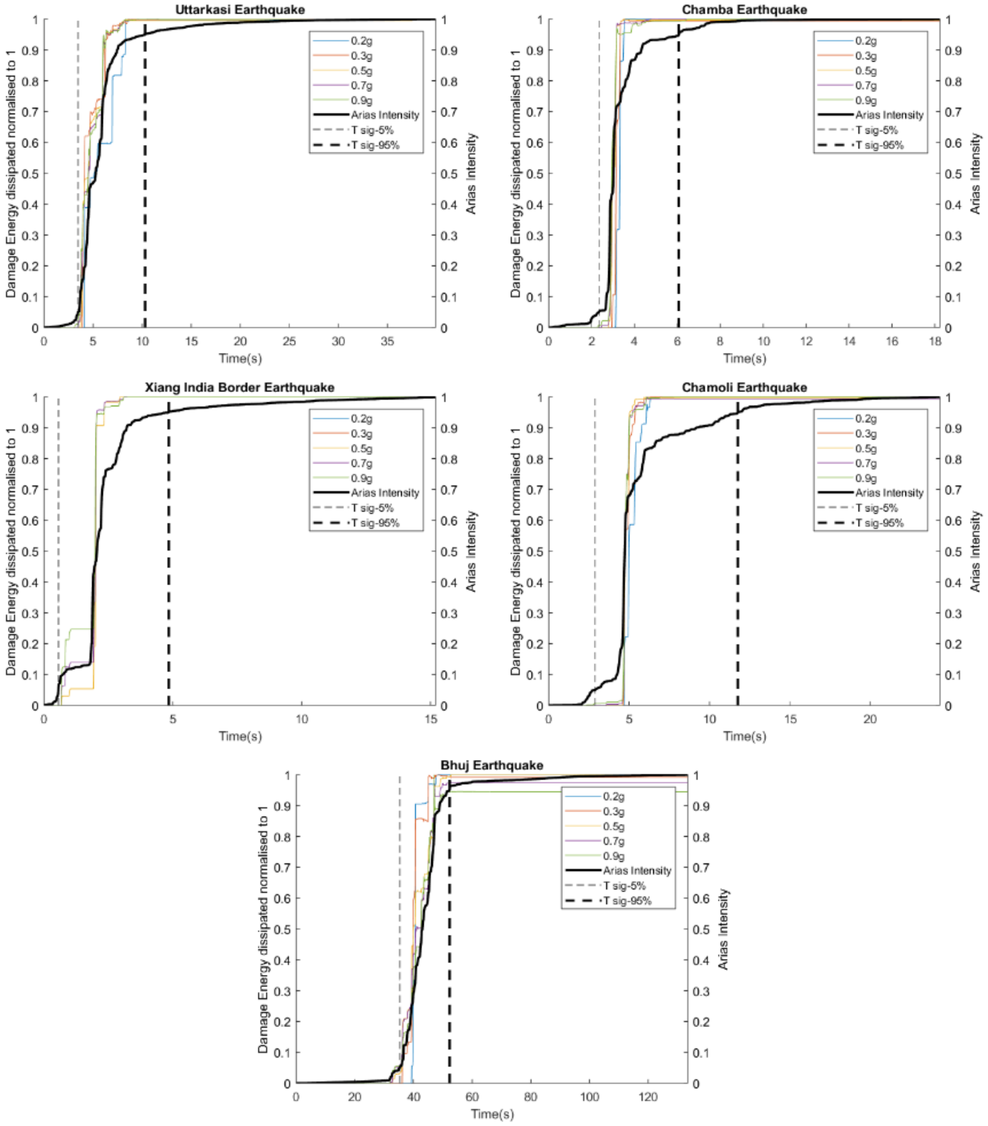
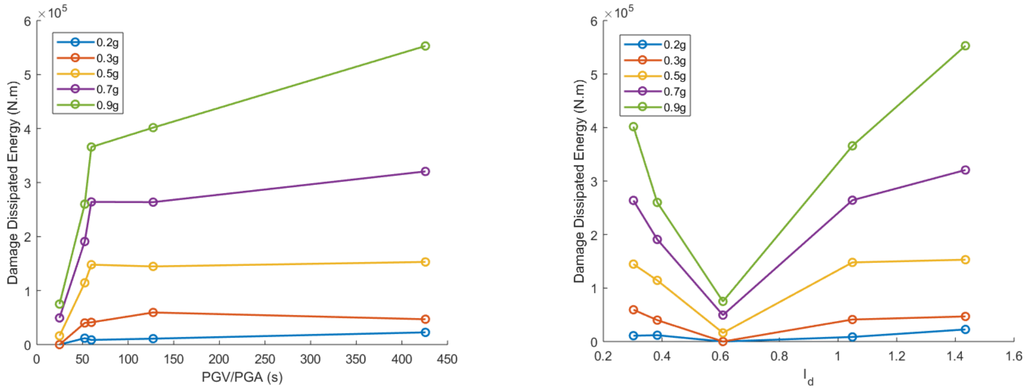


Fig. 7 – Arias intensity and Normalized Damage dissipated energy for chosen ground motions

The Damage dissipation energy is enveloped completely by $T_{sig-5\%}$ and $T_{sig-95\%}$. Arias intensity curve gives us a vague idea of the damage dissipation energy profile of the dam. Arias Energy curve, $T_{significant}$ are properties of the ground motion. Damage dissipated energy is purely related to the material characteristics of the structure.



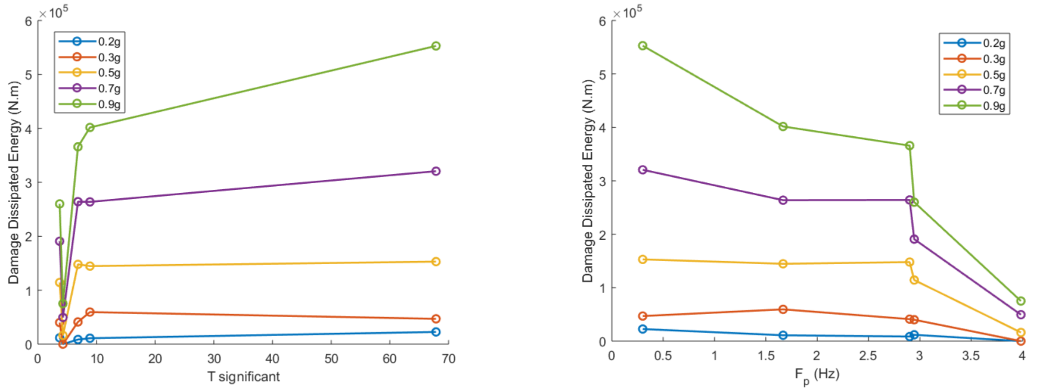


Fig. 8 – DDE versus Amplitude static GMPs

The resemblance between the two suggests a strong correlation between ground motion parameters and response of structure.

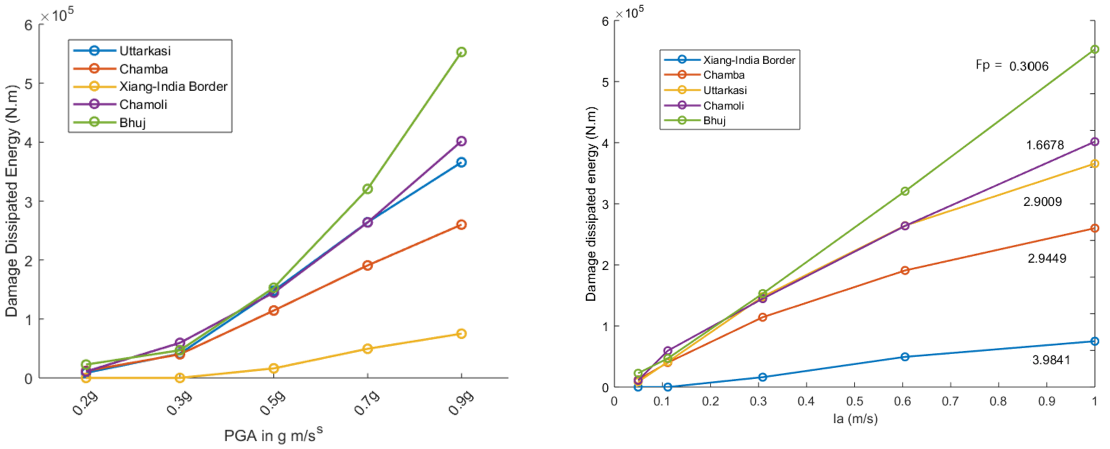


Fig. 9 PGA dependent GMPs v/s Damage dissipated Energy

a) PGA v/s DDE b) I_a v/s DDE

PGA dependent GMPs are directly proportional to damage. In both cases shown in Fig. 9 we see that the Damage dissipated energy increases with increase in the PGA dependent GMP. PGA independent GMPs as shown in Fig 8. cannot be directly correlated to Damage dissipation energy. F_p and PGV/PGA are proportional to damage dissipated energy but not I_d and T_{sig}. Fig 9b) shows us the relation between **damage dissipated energy (DDE), Ia and Fp.** Line fitting Fig. 9b) we get $y = mx + c$ where m is dependent on F_p and x is I_a .

Thus,

$$DDE \propto I_a \quad and \quad DDE \propto \frac{1}{F_p} \quad \Rightarrow \quad DDE \propto \frac{I_a}{F_p}$$

$$DDE \ = \ k.\frac{I_a}{F_p} \ + \ c$$

where k and c are constants. $k = 1.47 * 10^6$ and $c = -4.38 * 10^4$.

Hence for the above data, $DDE = 10^6 \times \left(1.47 I_a / F_p - 4.38\right)$

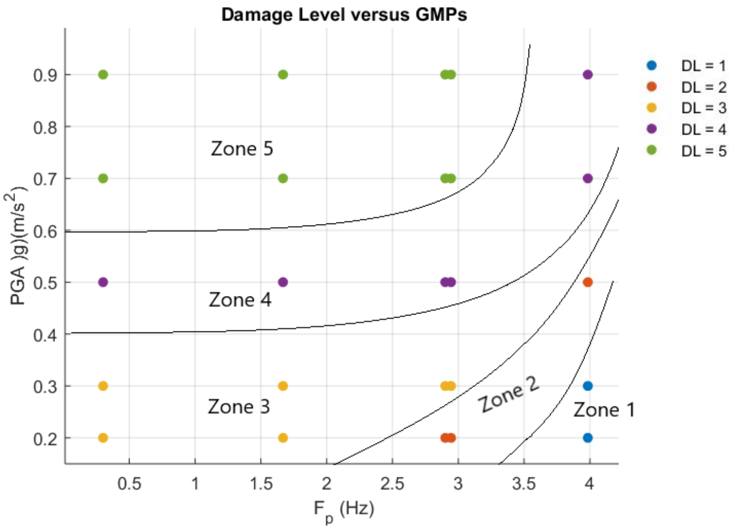


Fig. 10 – Variation of Damage Levels (DL) along F_p and PGA.

Fig.10 shows the variation of damage levels, as discussed in Section 6, along the ground motion parameters PGA and F_p. The 5 zones enveloped by the curves show the tuple $< F_p, PGA >$ with the corresponding Damage Level (DL). At PGA = 0.2g we see that with increasing frequency F_p the damage level covers 3 zones. DL=1, denoting negligible damage, DL = 2, denoting slight damage with minor repair, and DL=3, denoting medium damage with major repair, all fall under 0.2g PGA.

8. Conclusion

The objective of this study is to analyze the effect of strong ground motions on the damage to the dam. Comparing GMPs to EDPs, as done here, enables us to design structures based on the performance. Amplitude, Frequency and Time have a significant effect on the response of the dam. While amplitude and significant time factors are directly proportional to the damage, frequency is inversely proportional to damage. Most design codes take only the PGA into account. But frequency and duration of ground motion also highly influence the performance of the dam. For the selected ground motions, PGA and F_p played an equally important role in the damage. Even at a low PGA of 0.2g, the damage is profound for lower frequencies while it is negligible for higher frequencies. The correlation between ground motion parameters and the damage to the structure affirm the need for site specific design of structures. Based on the design of structure and the site parameters, the damage can be predicted.

8. References

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