Performance of Concrete Gravity Dam Under Seismic Loads with Incremental Dynamic Analysis at Varying Dam Height

Asmidar Mohamad, Nik Zainab Nik Azizan

Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia

ABSTRACT

Concrete gravity dam is a significant infrastructure in the country that plays a pivotal role to the community. This paper investigates the performance of concrete gravity dams with different heights under seismic load through Incremental Dynamic Analysis (IDA). The methodology employed in this study involves a selection of seven ground motions and a nonlinear numerical analysis model using the material properties from the Koyna dam. Through the analysis, a fragility curve was developed to identify the damage states at different ground motion intensity levels. The displacement observed at the yielding state of 50m dam is measured as 25.93mm, 75m dam is 31.50mm, 100m dam is 36.50mm and 50.46mm for 125m dam. In comparison, the ultimate state of the 50m dam is 40.20mm, 75m dam is 41.89mm, 100m dam is 48.45mm and the 61.96mm for 125m dam. This finding indicates that the level of damage is influenced by the height of the dam with taller dams having a greater impact.

Keywords: Thesis, concrete gravity dam, IDA analysis, seismic load.

1. INTRODUCTION

Concrete gravity dams are one of massive structures that are built for various functions such as flood control, hydroelectric power generation, agricultural work, water resource conservation, fish and wildlife enhancement, recreation, etc. It was built a decade ago for its service. However, it is usually constructed near populated areas, which causes a high risk to the surroundings due to strong ground motion during earthquake events that release uncontrolled water from the reservoir, endangering the people and properties.

An earthquake is a violent vibration of the Earth's surface caused by releasing energy from the Earth's crust. Quickly sliding on a fault or a crack in the Earth's crust can generate this energy. Vibrations known as "seismic waves" are produced during the quick slip. The speed at which these waves travel outward from the earthquake's source along the surface and through the Earth varies depending on the material through which they pass.

Some cases in India became case studies for many researchers regarding the dams, which as the Koyna gravity dam in 1967. Also in China which is The catastrophic earthquake in Wenchuan of the Sichuan Province on May 12, 2008 (magnitude 8.0), in Yushu of the Qinghai Province on April 14, 2010 (magnitude 7.1) and in Lushan of the Sichuan Province on April 20, 2013 (magnitude 7.0) [1]. The seismic response of concrete dams is affected by various factors such as, interaction with the reservoir and foundation, compressibility of reservoir water, an appropriate truncation boundary condition to formulate the infinite reservoir at the upstream side, effect of surface waves (sloshing waves), absorption of acoustic waves at reservoir bed due to sedimentary material etc [2]. Dam failure can occur if the reservoir level experiences dangerous fluctuations while an earthquake is also taking place. A concrete dam's failure can have devastating effects on nearby communities due to the rapid release of the reservoir. Earthquakes have damaged several concrete dams, but no collapses have been reported. But some dams have been badly damaged. There were several dams failures or major damages due to the earthquake [3] such as Koyna dam in 1967 India, Shih Kang dam in 1999 Taipei, Hsinfengkiang dam in 1962 China, Sefid-Rud Dam in 1990 Iran, Pacoima dam 1971 and 1994 USA, Uh dam Japan.

Since the damage to Koyna Dam in India in 1967, which has been recognized as one of the most investigated studies to evaluate the seismic performance of concrete gravity dams all over the world [4]–[8], the seismic safety of such dams has been a severe worry. As a result, the Koyna Dam was chosen as the case study for this research. There is various heights of dams have been designed and greater damage occurred on higher dams such as Koyna Dam with 103 m in height. Whereas the highest dam is Jin'anqiao Dam, which stands at 112m [1]. [9] in their study stated that the limiting height of a low-gravity dam is 90 m. As a result, the preliminary height of the high dam is increased to 95 m to designate it as a high dam. A freeboard of 5 m equals about 4% - 5% of the dam height is considered. Finally, for stability and stress assessments, the dam's entire height including freeboard is 100 m. IDA have been widely used by many researchers such as [10], [11][11]–[13] [14]–[16] In the framework of performance-based earthquake engineering, the assessment of demand and capacity is viewed through the lens of an IDA study. [17] in his study using the IDA to perform seismic fragility analysis of the Koyna dam and the result shows that the tensile carks initially appear in the neck or heel region of the dam and later in the main body of the dam.

The objective of this study is to investigate the concrete gravity dam performance by using the incremental dynamic analysis (IDA), the development of damage to this concrete gravity dam was examined at various heights between 50m, 75m,100m and 125m dams. Furthermore, with these methods, various limit states were determined.

2. EXPERIMENTAL PROCEDURE

In this present investigation, the performance of concrete gravity dam on nonlinear dynamic response was evaluated. Modelling of two-dimensional plane strain formulation was considered, and a concrete damage plasticity model was used [17][1]. Two main components are influenced by earthquake impact which are the height (H) of the concrete gravity dam and the base width (L) [12]. The dam was designed with a free board of 5% to the height of the dam and 5 variables were considered in the design. Dam dimension was calculated by equation (1) and (2) below [18]:

$$a = \sqrt{H_w} \quad (1)$$

Where H_w is the water height and a is the width of the top dam.

$$B = \frac{H}{\sqrt{(Sc-c)}} \quad (2)$$

The B = width of the base, H = dam height, Sc = concrete gravity and c=0 (when uplift disregarded).

2.1 Incremental Dynamic Analysis (IDA) Method

The IDA method was utilized in this study to determine the structure responses towards seismic behaviour. It provides results until the structure reaches its yielding and ultimate states. The flowchart of this method is presented in Figure 1.

In the incremental dynamic analysis (IDA) method, IDA curves are generated with the relative displacement angle on the x-axis (damage measure, DM) and peak ground acceleration (PGA) on the y-axis (intensity measure, IM). [1], [10], [19], [20]. IDA curves are generated by interpolating the findings of the time history analysis. A concrete damaged plasticity model (CPD) is used in

ABAQUS to access the nonlinear seismic pattern. ABAQUS has been the most used software for researchers to analyse the structure under seismic loads such as[21]–[24] Seven ground motion records are typically chosen. The Pacific Earthquake Engineering Research Center (PEER) database was used to obtain seven ground motion records from real earthquake events based on the gravity dam's site data and the standard for seismic design of hydraulic structures. The selected records accordance with the site characteristics and design response spectrum of the project. Each seismic wave adjusted the peak ground acceleration (PGA) to be equal to or greater than 0.15g according to a certain ratio, and introducing it into the nonlinear analysis model forced the structure from elastic response to final overall damage. Other criteria include near-fault ground motions with a distance of less than 15km, multiple events in the same direction and earthquakes with magnitudes equal to or greater than 5.5 that occur repeatedly. Many researchers use near-fault seismic load to investigate the damaging impact on concrete gravity dams [13], [25]–[27] Seismo signal software will be used to convert the seven ground motions' time history to the acceleration response spectrum. The acceleration ranging from 0.10g to 1.10g was selected. The design of the response spectrum was scale based on Eurocode 8 [28]. There were two types of equations which are vertical (1) to (4) and horizontal equations from (5) to (8) as per [28]:

Equation for vertical elastic response spectrum.

$$0 \leq \mathrm{T} \leq \mathrm{T_B}: S_{\mathrm{ve}}(T) = \mathrm{a}_{vg} \cdot S\left[\frac{\mathrm{T}}{\mathrm{T_B}} \cdot (\eta \cdot 3.0 - 1)\right]$$

$$\mathrm{T_B} \leq \mathrm{T} \leq \mathrm{T_C}: S_{ve}(T) = \mathrm{a}_{vg} \cdot S \cdot \eta \cdot 3.0$$

$$\mathrm{T_C} \leq \mathrm{T} \leq \mathrm{T_D}: S_{ve}(T) = \mathrm{a}_{vg} \cdot S \cdot \eta \cdot 3 \cdot 0\left[\frac{\mathrm{T_C}}{\mathrm{T}}\right]$$

$$\mathrm{T_D} \leq \mathrm{T} \leq 4\mathrm{s}: S_{ve}(T) = \mathrm{a}_{vg} \cdot S \cdot \eta \cdot 3.0\left[\frac{\mathrm{T_C T_D}}{\mathrm{T^2}}\right]$$

Equation of horizontal elastic response

$$0 \leq \mathrm{T} \leq \mathrm{T_B}: S_{\mathrm{ve}}(T) = \mathrm{ag} \cdot S\left[\frac{\mathrm{T}}{\mathrm{T_B}} \cdot (\eta \cdot 3.0 - 1)\right]$$

$$\mathrm{T_B} \leq \mathrm{T} \leq \mathrm{T_C}: S_{\mathrm{ve}}(T) = \mathrm{ag} \cdot S.\eta \cdot 3.0$$

$$\mathrm{T_C} \leq \mathrm{T} \leq \mathrm{T_D}: S_e(T) = \mathrm{ag} \cdot S \cdot \eta \cdot 2.5\left[\frac{\mathrm{T_C}}{\mathrm{T}}\right]$$

$$\mathrm{T_D} \leq \mathrm{T} \leq 4\mathrm{s}: S_{ve}(T) = \mathrm{ag} \cdot S \cdot \eta \cdot 3.0\left[\frac{\mathrm{T_C \cdot T_D}}{\mathrm{T^2}}\right]$$

Where $S_e(T)$ is elastic response spectrum, T is vibration period of a linear single-degree-of-freedom system. Whereas ag is type A ground on design ground acceleration. $\mathrm{T_B}$ refer as constant spectral acceleration branch at lower limit of the period. Then $\mathrm{T_C}$ is constant spectral acceleration branch at upper limit of the period. Next $\mathrm{T_D}$ is the value defining the beginning of the constant displacement response. S is the soil factor and lastly damping correction factor as η.

The Koyna dam has been considered as a case study with rigid foundation and details of material properties of Koyna dam is listed in Table 1. The seven ground motion data shown in Table 2 below and the response spectrum was obtained in Figure 2.

Table 1 Material parameters of Koyna Dam

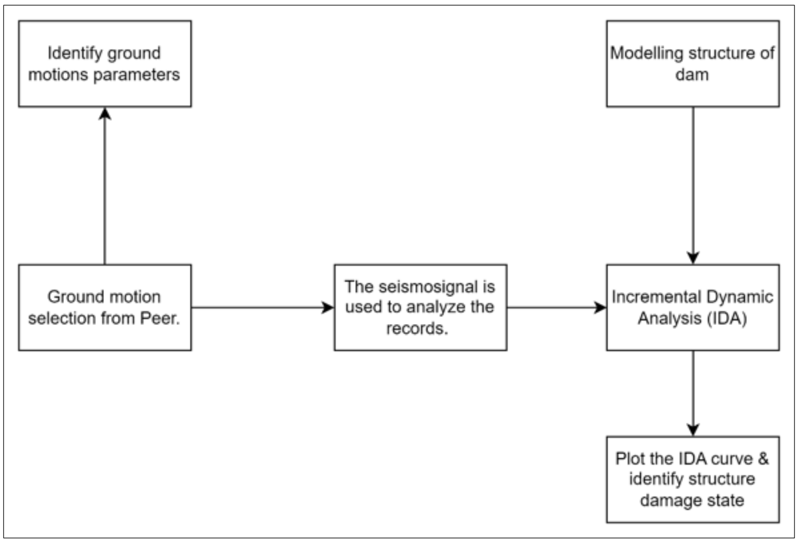

Figure 1 Flowchart of the Methodology

Table 2 Material parameters of Koyna Dam

Material properties	Value
Modulus of elasticity (E)	31513 MPa
Poisson's ratio (ν)	0.2
Density	2643 kg/m3
Dilation angle (ψ)	36.31˚
Compressive initial yield stress	13.0 MPa
Compressive ultimate stress	24.1 MPa
Tensile failure stress	2.9 MPa
Damping for the first mode vibration	3%

Table 3 Summary parameters of selected ground motions

No	Earthquake Name	Year	Station Name	Magnitude	Rjb (km)	PGA-H (g)	PGA-V (g)
1	Loma Prieta	1989	Saratoga - Aloha Ave	6.93	7.58	0.51446	0.3957
2	Kobe Japan	1995	Amagasaki	6.9	11.34	0.27578	0.34183
3	Imperial Valley 06	1979	Brawley Airport	6.53	8.54	0.16261	0.15281
4	Parkfield 02 CA	2004	Parkfield Work Ranch	6	10.33	0.3413	0.16974
5	Chi-Chi Taiwan	1999	Chy101	7.62	9.94	0.33966	0.1655
6	Landers	1992	Joshua Tree	7.28	11.03	0.27358	0.18096
7	Mammoth Lakes-03	1980	Convict Creek	5.91	2.67	0.23349	0.1726

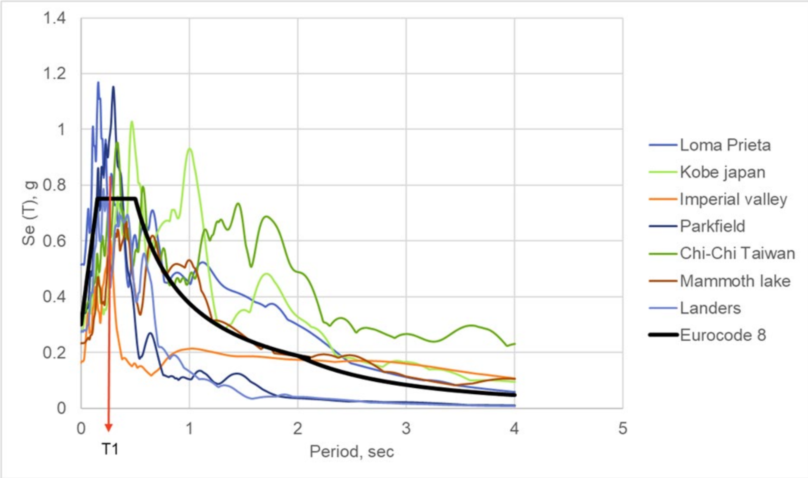

Figure 2 Scaling of ground motions to the same spectrum acceleration.

3. RESULTS AND DISCUSSION

At the 50m height of the dam, the damage profiles influenced by the PGA are depicted in Figure 3. It can be seen from that figure with 0.05g< PGA <0.70g indicating that the dam was in a slightly damage state. The yielding point of cracks started to appear at the downstream slope of the dam neck and heel. In accordance with Table 4, the maximum displacement of the average yielding value was 25.93mm. Whereas the ultimate state started to occur at 0.45g<PGA>0.90g with an average maximum displacement value was 40.20mm. The ultimate state began when the cracking line reached 50% of the dam width until the cracks extended and the structure collapsed. The IDA curved in Figure 4 illustrates seven single ground motions. The two dashed lines were the average point of yielding and ultimate state. The mean value shows at 0.35g at the yielding and 0.55g at the ultimate point. The same goes for the median value.

At the 75m height of the dam, the yielding limit state was between 0.20g<PGA<0.40 with a maximum displacement was 31.50mm. Meanwhile, the ultimate state was 0.25g<PGA>0.55 respectively with 41.89mm of maximum displacement as shown in Table 4. Figure 3 shows the formation of a few micro-crack path at the neck region and the dam heel when hitting the yielding point. However, when the PGA increased the dam started to form larger cracks around the upper and lower parts of the dam body. In the IDA curve based on Figure 5, the mean value at the yielding point was 0.37g and while the ultimate point is found to be 0.42g. However, it is slightly different to the median value.

At the 100m height of dam the yielding point began to crack starting from 0.15g<PGA<0.30g which is the first crack at 36.50mm of maximum displacement as tabulated in Table 4. As the PGA motion increased the dam continue to crack partially at 0.30g<PGA>0.40g onwards which considered as ultimate point at 48.45mm. Whereas the Figure 6 shows the IDA curve with mean value 0.18g at the yielding point and 0.24g at the ultimate point. In Figure 3 illustrate the cracking pattern around neck and based heel at first cracking and the formation of half of structure body when it reached the ultimate point.

At the 125m height of dam, when the structure starts to crack it's called the yielding state at 0.10g<PGA<0.20g around 20% from the dam width at 50.46mm of maximum displacement as stated in Table 4. While the occurrence of ultimate state began when the cracks reached 50% from the width dam with 0.15g<PGA>0.25g at 61.96mm. The cracking pattern of this dam can be seen through Figure 3 shows that at low PGA the cracking starting to form at neck region and extended heel base then went to the middle part of dam's body. [1] In their study on Jin'anqiao

Dam with 112m height stated that at the low PGA a few cracks already appeared at the head region and dam was still in intact state. Through this observation the higher dam caused the damaging speed increased compared to 50m height dam the cracking pattern profile corresponding to high PGA. The IDA curve shown in Figure 7 stated that mean value was 0.16g at yielding point and 0.22g at ultimate point. The median on the other hand had slightly different value.

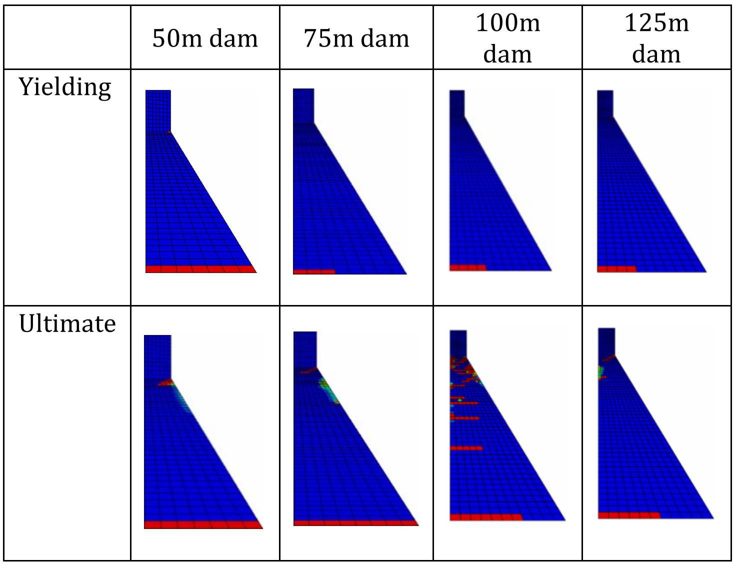

Figure 3. Cracking patterns and max displacement.

Table 4 Displacement of yielding and ultimate states of various dam height

Ground Motions	**Displacement**							
	50m dam		**75m dam**		**100m dam**		**125m dam**	
	Yielding (mm)	**Ultimate (mm)**	**Yielding (mm)**	**Ultimate (mm)**	**Yielding (mm)**	**Ultimate (mm)**	**Yielding (mm)**	**Ultimate (mm)**
Loma Prieta	24.39	22.16	25.12	40.51	18.41	40.69	45.48	56.85
Kobe Japan	24.46	40.63	33.76	44.24	42.59	46.91	43.25	48.78
Imperial Valley	24.83	60.22	25.18	34.12	34.96	44.66	48.69	58.01
Parkfield	21.40	32.19	44.21	53.76	48.71	62.52	44.31	64.47
Chi-chi Taiwan	34.91	47.48	35.59	40.93	50.53	58.12	60.22	72.02
Landers	21.68	32.83	24.94	38.60	24.50	38.97	57.10	69.36
Mamoth Lake	29.86	45.88	31.73	41.07	35.83	47.30	54.19	64.24
Average	25.93	40.20	31.50	41.89	36.50	48.45	50.46	61.96

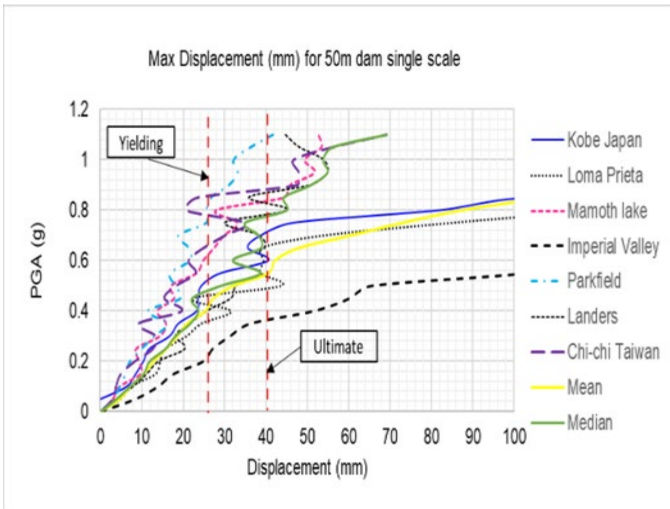

Figure 4. IDA curve of 50m dam.

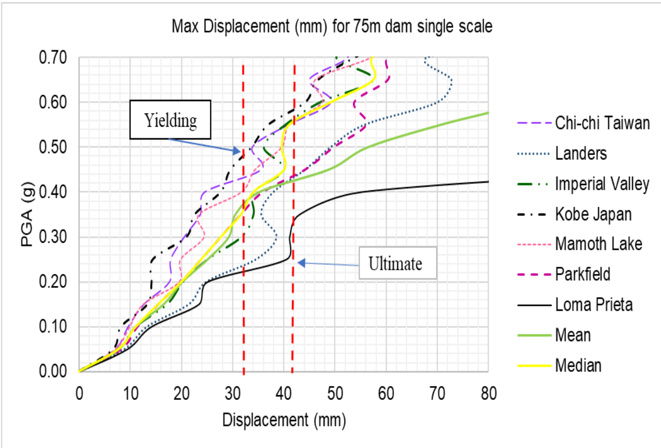

Figure 5. IDA curve of 75m dam.

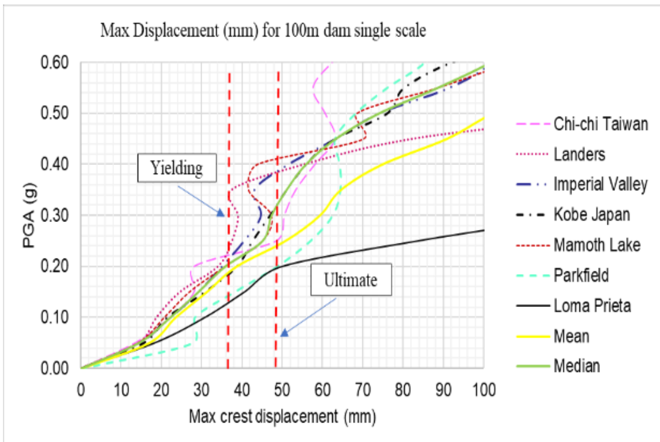

Figure 6. IDA curve of 100m dam.

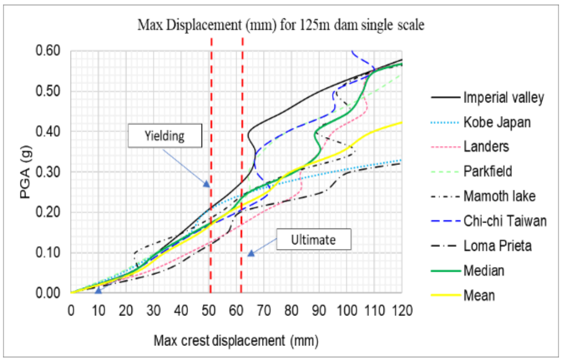

Figure 7. IDA curve of 125m dam.

4. CONCLUSION

In conclusion, IDA analysis is a good tool to evaluate the earthquake performance of concrete gravity dams. This analysis consists of a series of ground motion records that are scaled with escalating intensity until it achieves its final state. The crack patterns were observed through analysis starting from the minor cracks to the formation of the whole dam. In this finding, we conclude that the comparison between the dam was the higher the dam caused more damage. Thus, we could enhance our understanding of the structure safety and design, which is able to withstand this during earthquake events.

REFERENCES

[1] D. H. Chen, Z. H. Yang, M. Wang, and J. H. Xie, “Seismic performance and failure modes of the Jin’anqiao concrete gravity dam based on incremental dynamic analysis,” *Eng Fail Anal*, vol. 100, pp. 227–244, Jun. 2019.

[2] S. Gorai and D. Maity, “Seismic response of concrete gravity dams under near fi eld and far fi eld ground motions,” *Eng Struct*, vol. 196, no. April, p. 109292, 2019.

[3] P. Nayak and D. Maity, “Seismic Damage Analysis of Aged Concrete Gravity Dams,” no. August 2013, 2015.

[4] A. Tiwari, A. Issa, and M. S. Alam, “Comparative seismic performance of Koyna and Corra Linn dams using Comparative seismic performance of Koyna and Corra Linn dams using numerical analysis and shake table testing,” no. March, 2020.

[5] J. Rodríguez *et al.*, “Comparative seismic performance of Koyna and Corra Linn dams using numerical analysis and shake table testing,” 2020.

[6] H. Mazighi and M. K. Mihoubi, “Damage of a concrete gravity dam under the effect of the hydrodynamic loads,” *Procedia Structural Integrity*, vol. 42, pp. 1714–1720, 2022.

[7] M. S. Pourbehi, G. P. A. G. van Zijl, and J. A. vB. Strasheim, “Analysis of combined action of seismic loads and alkali-silica reaction in concrete dams considering the key chemical-physical-mechanical factors and fluid-structure interaction,” *Eng Struct*, vol. 195, pp. 263–273, Sep. 2019.

[8] R. K. Srivastava and D. R. Sahoo, “Seismic analysis of a concrete gravity dam considering dam-water-sediment-foundation interaction,” *Dams and Reservoirs*, vol. 33, no. 1, 2023.

[9] Md. H. Ali, M. R. Alam, M. N. Haque, and M. J. Alam, “Comparison of Design and Analysis of Concrete Gravity Dam,” *Natural Resources*, vol. 03, no. 01, pp. 18–28, 2012.

[10] A. Majdi and A. J. Rahman, “Identify the limit states of hashazini dam by applying incremental dynamic analysis,” in World Congress on Civil, Structural, and Environmental Engineering, Avestia Publishing, 2019.

[11] L. He, D. Chen, Z. Yang, N. Yang, and B. Sun, "Study on seismic performance of three dimensional concrete gravity dam system based on IDA," *Journal of Natural Disasters*, vol. 28, no. 4, 2019.
[12] S. G. Gavabar and M. Alembagheri, "A Study on Seismic Performance and Fragility of Gravity Dams with Various Monolith Shapes Using Nonlinear IDA," *Geotechnical and Geological Engineering*, vol. 38, no. 2, 2020.
[13] S. Xu, Q. Xu, J. Chen, and J. Li, "Improved endurance time analysis for seismic responses of concrete dam under near-fault pulse-like ground motions," *Eng Struct*, vol. 270, 2022.
[14] D. Vamvatsikos and C. Allin Cornell, "Incremental dynamic analysis," *Earthq Eng Struct Dyn*, vol. 31, no. 3, pp. 491–514, 2002.
[15] T. Tasnim Nahar, A.-T. Cao, and D. Kim, "Risk Assessment of Aged Concrete Gravity Dam Subjected to Material Deterioration Under Seismic Excitation," *Int J Concr Struct Mater*, vol. 14, p. 53, 2020.
[16] G. Sevieri, A. De Falco, M. Andreini, and H. G. Matthies, "Hierarchical Bayesian framework for uncertainty reduction in the seismic fragility analysis of concrete gravity dams," *Eng Struct*, vol. 246, Nov. 2021.
[17] A. R. Tidke and S. Adhikary, "Seismic fragility analysis of the Koyna gravity dam with layered rock foundation considering tensile crack failure," *Eng Fail Anal*, vol. 125, Jul. 2021.
[18] Garg SK, Design and construction of gravity dams. In: Irrigation engineering and hydraulic structures. Khanna, 2009.
[19] B. F. Soysal, B. Binici, and Y. Arici, "Investigation of the relationship of seismic intensity measures and the accumulation of damage on concrete gravity dams using incremental dynamic analysis," *Earthq Eng Struct Dyn*, vol. 45, no. 5, 2016.
[20] K. Mahmoodia, A. Noorzad, and A. Mahboubib, "Seismic fragility analysis of a cemented Sand-gravel dam considering two failure modes," *Computers and Concrete*, vol. 26, no. 6, 2020.
[21] S. Sarkhel, J. Padhi, and A. K. Dash, "Seismic Analysis of a Concrete Gravity Dam Using ABAQUS," in Lecture Notes in Civil Engineering, vol. 75, Springer, 2021, pp. 253–263.
[22] X. Zheng and J. Hao, "Research on Seismic Assessment of Gravity Dam Based on Performance Analysis," in IOP Conference Series: Earth and Environmental Science, Institute of Physics Publishing, Dec. 2019.
[23] S. Gorai and D. Maity, "Seismic Performance Evaluation of Concrete Gravity Dams in Finite-Element Framework," *Practice Periodical on Structural Design and Construction*, vol. 27, no. 1, Feb. 2022.
[24] H. Mohammadnezhad, M. Ghaemian, and A. Noorzad, "Seismic analysis of dam-foundation-reservoir system including the effects of foundation mass and radiation damping," *Earthquake Engineering and Engineering Vibration*, vol. 18, no. 1, 2019.
[25] Y. Zhai, L. Zhang, B. Cui, H. Zhang, and T. Ma, "Evolution criteria of overall damage of concrete gravity dam body and foundation under near-fault ground motion," *Structures*, vol. 43, no. July, pp. 594–605, 2022.
[26] S. Gorai and D. Maity, "Seismic response of concrete gravity dams under near field and far field ground motions," *Eng Struct*, vol. 196, Oct. 2019.
[27] A. Y. Rasa, A. Budak, and O. A. Düzgün, "Seismic Performance Evaluation of Concrete Gravity Dams Using an Efficient Finite Element Model," *Journal of Vibration Engineering and Technologies*, 2023.
[28] British Standards Institution., European Committee for Standardization., and British Standards Institution. Standards Policy and Strategy Committee., Eurocode 8, design of structures for earthquake resistance. British Standards Institution, 2005.