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RESEARCH ARTICLE

Seismic Performance of Concrete Gravity Dam Under Varying Water Level and Dam Height

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ABSTRACT - Concrete gravity dam is a massive structure that uses its weight to resist the forces. However, strong ground motions can lead to the structure's failure. Using the material properties of the Koyna dam, a 2D nonlinear numerical analysis model is developed in ABAQUS Software using the Concrete Damage Plasticity (CDP). The Incremental Dynamic Analysis (IDA) was performed to obtain the IDA curve for the concrete gravity dam, considering variations in dam height and water level in response to single and repeated earthquake events. Seven ground motions were scale as per the Eurocode 8. IDA curves were generated to illustrate the damage states at various ground motion intensities. The result at 50 m dam the ultimate displacement range from 28.04 mm at (full, single) to 39.31 mm (half, repeated). As for the 100m dam the maximum displacement increased from 48.45mm (full, single) to 54.59 mm (half, repeated). It shows that the higher dam receives significantly greater damage due to greater mass. Subsequently, dams with lower water level reduced the hydrostatic resistance caused to higher displacement. Furthermore, the dam received greater destruction due to repeated earthquakes than a single earthquake event. This finding emphasize the needs of incorporating the water levels, dam height and repeated seismic load in dam safety design and retrofitting strategy.

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1. INTRODUCTION

Concrete gravity dams are vital for water resource management, hydroelectric power generation, and flood control. Their stability and structural integrity are crucial to prevent severe consequences such as economic losses and potential loss of life [1]. Recent research indicates that repeated seismic events can cause cumulative damage that may not be apparent after a single event. The destructive potential of repeated earthquake events on structures has been the subject of numerous investigations by other researchers[2], [3] . [4] have highlighted that multiple seismic events can significantly affect the structural integrity of dams over time, a factor not fully accounted for in traditional seismic assessments. [5] further demonstrate that repeated seismic loading can lead to progressive deterioration, potentially compromising the safety of dams if not adequately addressed in design and analysis practices. Many researchers investigate the effect of repeated ground motions in various structures, for instance, in buildings, by [6], [7] and in dams [4], [8], [9]. However, most studies focus on certain heights of dams, while comparing different heights of dams is a limit case under different water levels and ground motions. All the parameters may cause different damage towards the dam.

In addition to seismic loading, the water level in a dam's reservoir and elevation significantly influence the seismic response towards the structure[10], [11]. Elevated water levels increase hydrostatic pressure on the dam structure, amplifying the effects of seismic forces. Seasonal fluctuations and operational changes in water levels add complexity to seismic analysis, as varying water levels can alter the dam's response to earthquakes in ways not always considered in current design standards [12].

Given these findings, there is a critical need to investigate the performance of concrete gravity dams under both single and repeated earthquake conditions, considering different water levels. This study aims to bridge the gap by evaluating a detailed analysis of the seismic performance of concrete gravity dams of different heights and water levels subjected to repeated seismic events. The main objective is to evaluate dam performance under seismic load with the effect of two water levels and dam height. The result later determines the failure mechanism based on crack patterns and displacement. A 2D plain strain nonlinear numerical model was developed in Abaqus by using the concrete damage plasticity model (CDP). In order to assess the seismic performance of structural capacity, the Incremental Dynamic Analysis (IDA) by [13]was adopted. The results are expected to lead to more accurate risk assessments and the development of improved design and retrofitting strategies to enhance the resilience of these essential structures.

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2. METHODS AND MATERIALS

2.1 Model Development

The performance of a concrete gravity dam on nonlinear dynamic response was evaluated. A concrete damage plasticity model was used [14] and modelling of a two-dimensional plane strain formulation was considered with two translational degrees of freedom at vertical and horizontal movement in the plane. Two dam heights at 50m and 100m were analysed. The model was subjected to hydrostatic pressure at two water levels (full and half). The foundation is assumed to be rigid with fixed boundary conditions at the base. The dam dimension was calculated by equations (1) and (2) below by [15]:

$$A = \sqrt{H_w} \tag{1}$$

$$B = [H_w / (\sqrt{S_c} - C)] \tag{2}$$

where H_w is the water level of the dam, A is the top width of the dam, B is the bottom width of the dam, S_c is the specific gravity of the concrete and C is the uplift coefficient = 0 (uplift pressure is ignore), the freeboard of the dam was considered 5% of the dam height.

The concrete gravity dam's material properties are taken from the Abaqus Example Problems Manual [16] and are assumed to be the same as the concrete used in the Koyna Dam. Table 1 shows the material properties of Koyna Dam, Figure 1 shows the typical geometry of concrete gravity dam and Table 2 shows the measurements of the concrete gravity dam’s cross-section.

Table 1. Material properties of the concrete gravity dam [16]

Material Parameter	Value
Modulus of elasticity (E)	31513 MPa
Poisson’s ratio (v)	0.2
Density (ρ)	2643 kg/m^3
Dilation angle (ψ)	36.31°
Compressive initial yield stress (σ_{c0})	13.0 MPa
Compressive ultimate stress (σ_{cu})	24.1 MPa
Tensile failure stress (σ_{t0})	2.9 MPa
Beta damping	0.00323

Table 2. Measurements of the concrete gravity dam’s cross-section

Height of dam, H (m)	Freeboard, F (m)	Water level, H_w (m)	Top width, A (m)	Bottom Width, B (m)
50	2.50	47.50	6.89	41.34
100	5.00	95.00	9.75	82.69

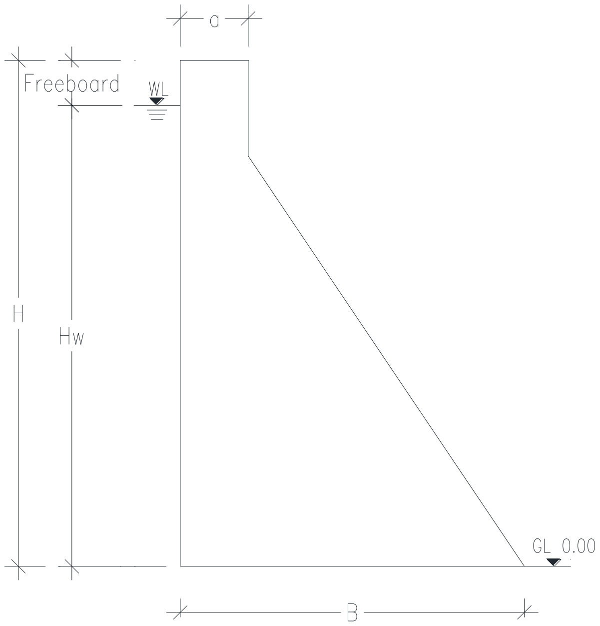


Figure 1. Design of concrete gravity dam

2.2 Model Validation

The precision of the present model with the existing result is crucial. In this study, the validity of the present numerical model is shown in Table 3 with differences of less than 3% compared to the result obtained by [17]

Table 3. Validation of numerical model

Mode	Natural Frequencies (rad/sec)		
	Present study	[17]	% of deviation
1	18.86	19.27	2.13
2	50.08	51.50	2.76
3	68.17	67.56	-0.90
4	98.71	99.73	1.02

2.3 Incremental Dynamic Analysis (IDA)

In this study, Incremental Dynamic Analysis (IDA) were chosen to evaluate the seismic performance of a concrete gravity dam. The ground motions listed in Table 3 were obtained from the database of the Pacific Earthquake Engineering Research Centre (PEER). In this study, several parameters were adopted, such as magnitude greater than 5.5, a peak ground acceleration (PGA) of at least 0.15g, and a near-field distance (R) less than 15 km from the earthquake source. Near-fault ground motion caused severe damage to the structure and has been investigated by many researchers concerning concrete gravity dams [5], [18], [19]. The assessment of the seismic effect on dams was identified by the IDA and used widely by numerous researchers [20-23]. Scaling of ground motions' intensity measure (IM) and damage measure (DM) is necessary to create an IDA curve. This study uses PGA(g) as an Intensity Measure (IM) based on ground motions and increasing scale factor with peak ground acceleration. By considering the maximum crest displacement (mm) as a Damage Measure (DM), the dam's limit states were determined. The dam's natural frequency, f, is determined by using ABAQUS, where 1/f can be used to compute the fundamental period, T1. The ground motion was scaled to obtain the elastic response spectrum by Eurocode 8 [24]. Every ground motion's acceleration response spectrum was scaled to the same pseudo-spectrum acceleration at the structure's fundamental period. The acceleration ranged from 0.10 g to 1.10 g with increments of 0.10 g every interval selected. A series of ground motions are applied to the dam, increasing in intensity gradually until the structure fails. Table 3 shows the ground motion data obtained from PEER.

Table 3. Summary of selected ground motion records

No	Earthquake Name	Year	Type of Ground Motion	Magnitude (M)	Rjb (Km)	PGA-H (g)	PGA-V (g)
1	Loma Prieta	1989	(Single)	6.93	7.58	0.514	0.396
			(Repeated)	6.93	8.65	0.511	0.556
2	Chi-Chi Taiwan	1999	(Single)	7.62	9.94	0.340	0.166
			(Repeated)	6.30	8.34	0.080	0.037
3	Kobe Japan	1995	(Single)	6.90	11.34	0.276	0.342
			(Repeated)	6.90	7.08	0.483	0.387
4	Imperial Valley 06	1979	(Single)	6.53	8.54	0.163	0.153
			(Repeated)	5.62	9.39	0.151	0.118
5	Parkfield 02 CA	2004	(Single)	6.00	10.33	0.341	0.170
			(Repeated)	6.00	6.27	0.251	0.184
6	Landers	1992	(Single)	7.28	11.03	0.273	0.181
			(Repeated)	7.28	2.19	0.725	0.823
7	Mammoth Lakes-03	1980	(Single)	5.91	2.67	0.233	0.173
			(Repeated)	5.94	6.44	0.266	0.190

3. RESULTS AND DISCUSSION

A total number of 240 analyses were carried out to obtain the crack patterns and maximum crest displacement of the concrete gravity dams with different heights and water level under single and repeated earthquake event. The IDA curve of each scenario of dam was plotted and analysed.

3.1 Limit State of 50 Dam

Figure 2 shows the crack patterns of the dams at limit state under single and repeated earthquake event. At 50m dam under full and half wáter level the the results indicate that failure of tensile cracking was found on two damage zones which at the base heel and the neck area. The initial crack formed from the neck region with small damage and full crack at the base showing the shear failure. When the structure cracking extends towards the dam upstream surface, The main body and heel base shows dam experiences the ultimate state with bigger displacement. At a 50m dam, Table 4 at full water level, the yielding state, the range starts from 0.05g< PGA <0.30g at 22.60mm, and the ultimate state is 0.15g<PGA>0.40g at 28.04mm under single ground motions. Whereas at repeated earthquakes, the yielding state starts from 0.15g< PGA <0.25g at 43.50mm, and the ultimate state is 0.25g<PGA>0.40g at 51.82mm.

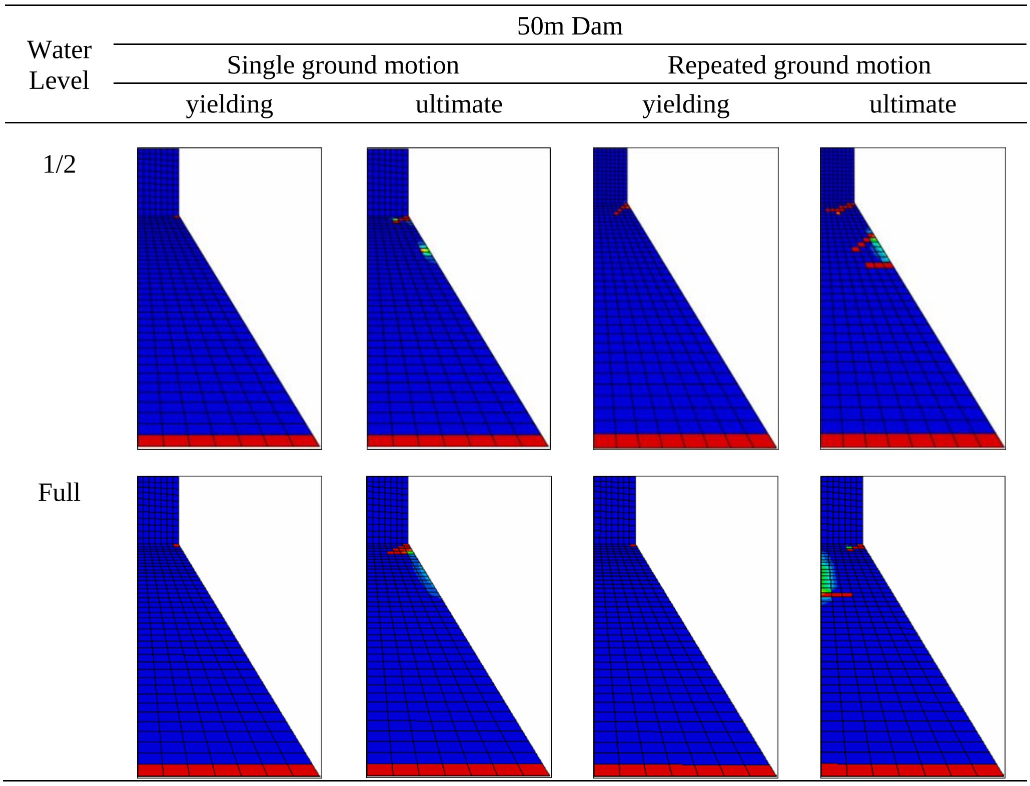
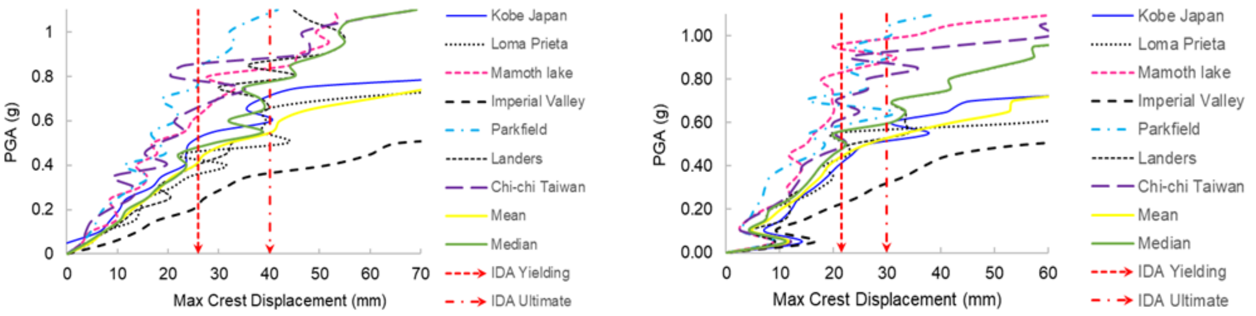


Figure 2. Crack paterns of 50m dam

Table 4. Maximum crest displacement at 50m dam

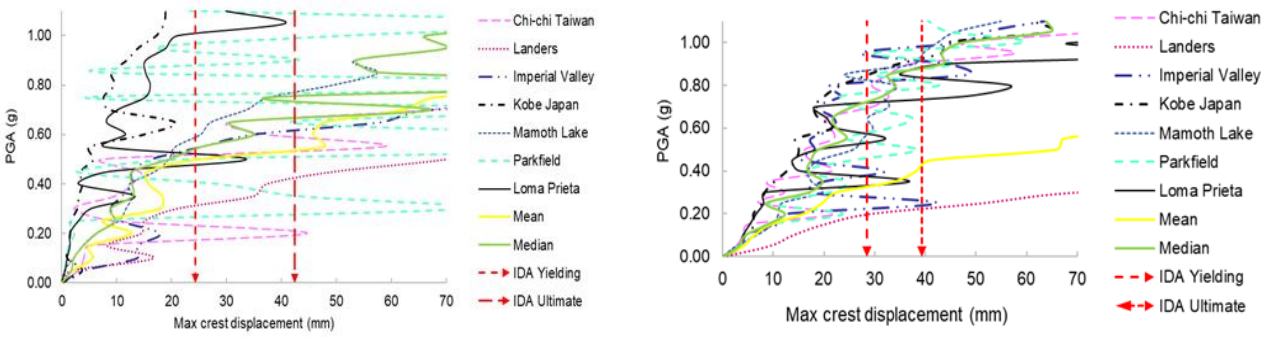
Displacement (mm)									
50 m dam									
No	Ground Motion	Single				Repeated			
		Full water level		Half water level		Full water level		Half water level	
		Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate
1	Loma Prieta	20.79	22.16	18.18	22.35	8.19	15.19	18.86	56.78
2	Chi-chi Taiwan	23.37	47.48	20.41	41.53	67.15	80.91	20.52	32.76
3	Kobe Japan	18.89	29.11	26.15	30.82	7.61	9.06	28.76	43.22
4	Imperial Valley	24.83	31.31	24.06	36.93	16.33	25.42	31.92	23.31
5	Parkfield	18.79	26.67	24.15	30.23	4.68	8.17	37.26	30.06
6	Landers	21.68	25.80	17.66	23.24	20.93	34.83	29.14	51.31
7	Mamoth Lake	29.86	33.19	20.04	24.68	37.70	53.42	32.26	37.71
	Average	22.60	28.04	21.52	29.97	23.51	32.43	28.46	39.31

As for half water height, the average maximum crest displacement at the yielding state and the ultimate state is 21.52 mm and 29.97 mm, respectively. Meanwhile, at repeated earthquakes, the average maximum crest displacement at the yielding state and the ultimate state is 28.46 mm and 39.31 mm, respectively. The IDA curve in Figures 3 and 4 illustrates the trend of maximum displacement under seven ground motions for both single and repeated earthquakes at a 50m dam. The displacement of the half-water level dam is greater than full water level dam at different water levels and ground motions. The water in a dam exerts a stabilising pressure against the structure. When the water level is lower, this stabilising pressure is reduced, making the dam more vulnerable to the dynamic forces of an earthquake [12].



(a) (b)

Figure 3. IDA curve of 50 m dam with (a) full water level; (b) half water level under single earthquake event



(a) (b)

Figure 4. IDA curve of 50 m dam with (a) full water level; (b) half water level under repeated earthquake event

3.2 Limit State of 100 Dam

At 100m dam Figure 5 shows the crack formation start at neck región with small damage on the base. This resulted from dam height where the tensile stress occurs in the upstream and downstream faces as the PGA increased. Under repeated scale, the crack formed at the neck and the base of dam at the PGA start from 0.20g. At half water level damage propagates more at neck and dam base.

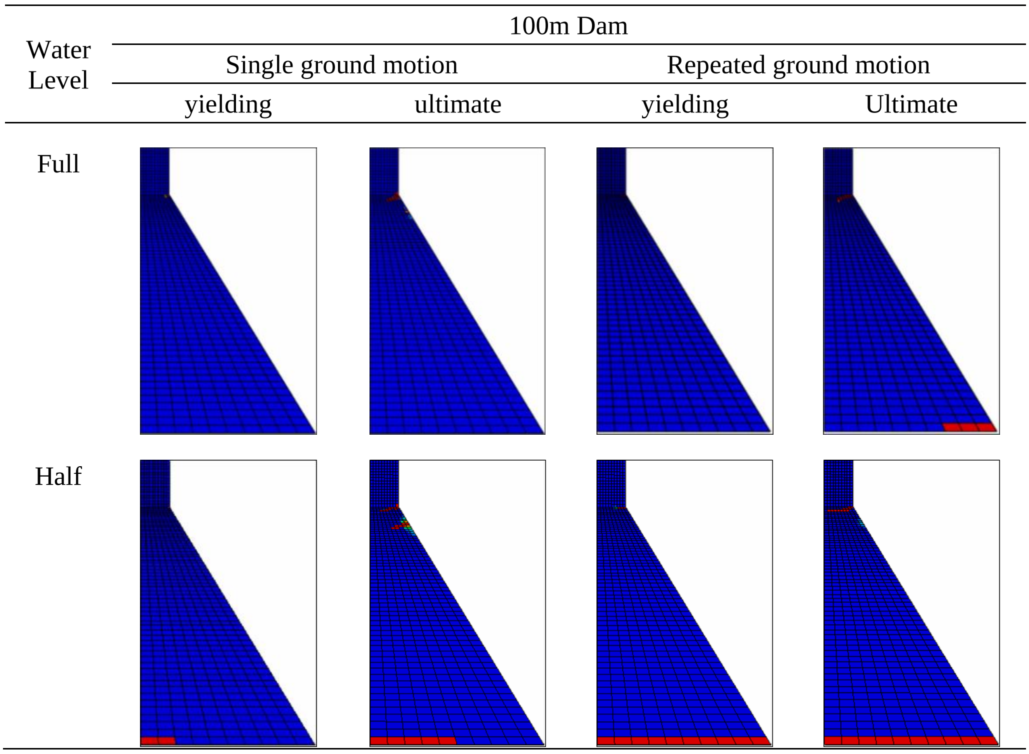
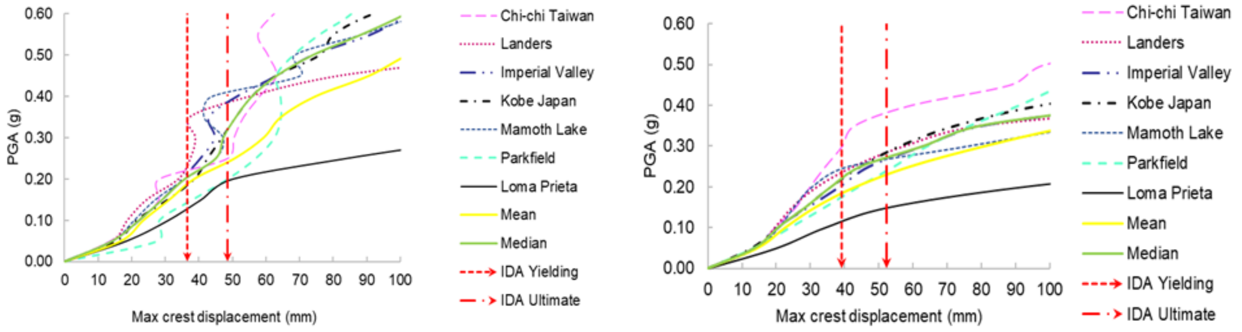


Figure 5. Crack patterns of 100 dam

Table 5. Maximum crest displacement at 100m dam

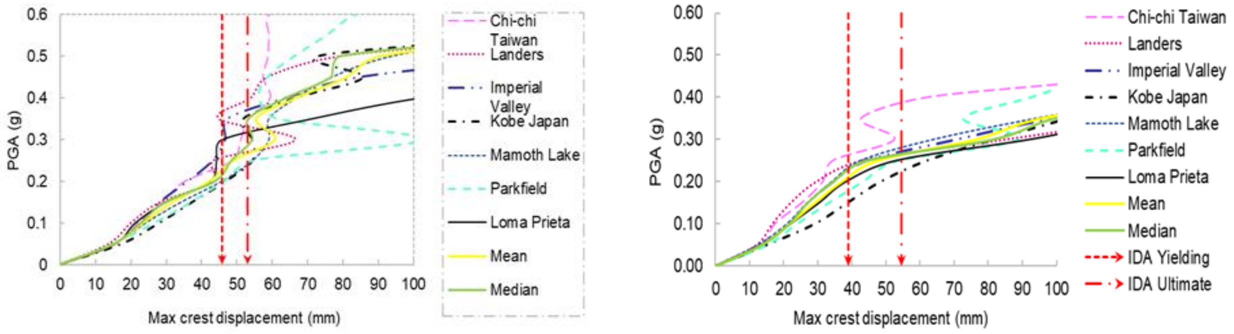
		Displacement (mm)							
		100 m dam							
		Single				Repeated			
No	Ground Motion	Full water level		Half water level		Full water level		Half water level	
		Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate
1	Loma Prieta	18.41	40.69	52.77	92.0	29.80	44.27	38.37	53.11
2	Chi-chi Taiwan	50.53	58.12	39.22	42.80	48.57	59.37	52.52	61.98
3	Kobe Japan	42.59	46.91	44.75	56.20	46.95	54.53	48.30	61.84
4	Imperial Valley	34.96	44.66	38.60	47.24	43.26	46.75	34.51	44.29
5	Parkfield	48.71	62.52	44.08	54.50	46.47	54.92	53.22	88.79
6	Landers	24.50	38.97	24.74	31.96	43.50	43.91	22.01	29.51
7	Mamoth Lake	35.83	47.30	30.37	40.86	45.57	59.01	34.20	42.59
	Average	36.50	48.45	39.22	52.22	43.50	51.77	40.45	54.59

The dam at 100m height model is a height structure, and it is crucial to understand the impact of seismic load. Additionally, the water level has a significant influence on the dam's performance. Table 5 shows the maximum displacement for both water levels under single and repeated ground motions. Under single ground motion, at full water level, the yielding state starts from $0.05g< \text{PGA} <0.30g$ at 36.50mm, and the ultimate state is $0.15g<\text{PGA}>0.40g$ at 48.45mm. However, at half water level, the displacement is higher, with 39.22mm and 52.22mm at yielding until it reaches its ultimate state. The trend same for the structure under repeated earthquakes that experience greater damage compared to a single earthquake event. Repeated seismic events can lead to the progressive weakening of the dam's materials and foundation. A single earthquake exhibits minor cracks and displacements and becomes worse by subsequent earthquakes. This progressive damage can compromise the dam's ability to withstand future earthquakes, making it more vulnerable to failure. The displacement of 100 m dam is significantly greater than 50m dam under both single and repeated earthquake events. According to [12] higher dams have a larger mass, which leads to greater inertial forces during an earthquake. These forces are proportional to the mass and the acceleration caused by the earthquake, resulting in higher stresses within the dam structure. Other researcher [25] showed that the same result was affected by low water levels cause more damage to the structure even with different ground motions.



(a) (b)

Figure 3. IDA curve of 100 m dam with (a) full; (b) half water level under a single earthquake event



(a) (b)

Figure 4. IDA curve of 100 m dam with full and half water level under repeated earthquake events

4. CONCLUSIONS

Through the analysis, the result reveals the performance of two different dam heights subjected to seismic effects. In conclusion, at yielding state occurred at an early PGA compared to the ultimate state at both dam heights. The initial cracks can be seen at the neck region and the base. Then propagated in the middle body until the collapse state. Damage from repeated ground motion is more severe than single ground motion. The higher dam receives significantly more damage during earthquakes. Dams with lower water levels received more damage as PGA increased compared to the full water level, as the pressure in the dam reduced its stability. Therefore, all the factors are necessary in the engineering aspect of implication. This study is significant for the improvement of structural safety at the design phase.

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CONFLICT OF INTEREST

The authors declare that no competing interest is related to the manuscript.

AUTHORS CONTRIBUTION

Asmidar Mohamad (Conceptualization, Methodology, Formal analysis, Software, Writing - original draft, Data Curation

Nik Zainab Nik Azizan (Methodology, validation, Data Curation, Funding acquisition; Project administration, Writing – review & editing, Supervision)

Shamilah Anudai @ Anuar (Investigation, Resources, Data Curation, Writing – review & editing, Supervision)

Tahara Ramadzan Md Kassim (Formal Analysis, Visualization)

Goh Duan Hao (Investigation, Resources, Formal Analysis)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study is available upon request from the corresponding author only.

ETHICS STATEMENT

It is not applicable as this study does not involve animal or human participation.

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