



Seismic evaluation of Karakaya Dam considering different ground motions

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Abstract

Damage to arch dams during a powerful earthquake can result in significant loss of life and property. Therefore, in order to prevent damage or destruction that may develop during a major earthquake, it is extremely important to determine how the arch dams will behave under the influence of earthquakes with different characteristics. For this reason, a parametric study is performed to determine the behaviour of Karakaya Dam under seismic loads by considering the different seismic conditions. Structural responses of Karakaya Dam under the influence of earthquakes with different characteristics were obtained and compared. It was determined that the different characteristics of ground motions are of great importance to the structural response of the dam. It was shown that the frequency content of seismic motions and earthquake properties are of great significance in terms of defining the seismic performance of the dam. It was revealed that changes in the structural behaviour forming in the dam body due to changes in ground motion, where the arch dams were sensitive to seismic records. In the formation of this difference, parameters such as peak ground acceleration, ground velocity, and frequency content of the earthquake have been shown to be effective. To determine the frequency matching between the structure and seismic motions, power spectra of seismic motions were obtained, and the frequency relationship between Karakaya Dam and ground motion was evaluated.

1. Introduction

Dams are important structures in terms of playing a vital role in water storage, irrigation, power production [1], electricity generation, reducing hazardous flooding, controlling river flow, etc. [2]. Water is one of the most important resources used for energy production, and many hydroelectric power plants have been built for this purpose. In hydroelectric power plants, water energy is converted into mechanical energy through water turbines. In other words, the energy resulting from the water level in the dam reservoir is potential energy, and when this flow energy reaches the turbine, it is converted into kinetic energy due to the acceleration effect that occurs. Mechanical energy is generated by the rotation of the turbine. Mechanical energy is converted into electrical energy and used. The efficiency of the turbine used during energy generation varies depending on the water flow rate, hydraulic drop, and hydraulic flow phenomena [3].

Dams can be constructed in regions with varying soil characteristics. Leakage problems may arise if the soil where

the dams are built is limestone. Marble-like rocks have a cracked, articulated, and faulted structure and may cause leakage problems due to the gaps they contain. Alluviums are loosely constructed and can be made of sand, clay, gravel, and silt layers [4].

Arch dams can be in wide V, narrow V, wide U, or narrow U shape depending on the terrain where they are constructed. The ratio of crest length to height is an important parameter from a design perspective. If the dam's height and central angle are constant, dams constructed in wide valleys exhibit more flexible structural behaviour than those constructed in narrow valleys, and the majority of the load is carried by cantilever action. Single-curve arch dams are dams that only have curvature in plan, while double-curve dams are dams that have curvature in both vertical and plan. In doubly curved dams, concrete is used more efficiently, and thinner dams are designed. The strength of these dams can be developed to their own weight; however, they also benefit from the arch

effect, which allows them to transfer the loads to the valley slopes [5].

During an earthquake, an interaction emerges between the dam and the elements supporting the dam. Openings in the dam body as well as supporting elements significantly affect the integrity of the dam [6]. When a dam damaged during an earthquake is also exposed to aftershocks, cumulative damage takes place in the system. If necessary repairs are not carried out on a structure damaged after a major earthquake, the risk of collapse and structural damage may increase. In order to reduce structural damage and collapse situations, it is important to carry out studies on the determination of the behaviour of the systems under the main earthquake and aftershock effects [7].

The selection of earthquake parameters is crucial during seismic investigations. In dam structures subjected to strong ground motions, conditions such as settlement, cracking, excessive displacement, and collapse are taken into consideration, and factors such as joint opening, shear, and tensile stresses are also evaluated in the seismic safety assessment of concrete dams [8].

Seismic loads can lead to damage and failure in dams. The Wenchuan earthquake ($M_s = 8.0$), which took place on 12 May 2008, caused damage to the Zipingpu concrete-faced rock fill dam. This dam is the first CFRD dam subjected to a magnitude IX earthquake, and studies related to this dam have been conducted [9]. In the 1967 Koyna earthquake, significant cracks formed in the Koyna concrete weight dam, and serious damage was induced [10]. In the Koyna earthquake (12.11.1967), a peak acceleration of 0.5 g in the transverse direction at the Koyna Dam was reached and resulted in significant cracks. While there was no sudden water release from the dam, it was decided to add concrete buttresses to the downstream sections of the monoliths due to these cracks [11]. The dams within the Van Norman Complex were affected by the 17 January 1994 Northridge earthquake ($M_w=6.7$). Strong movements were recorded at the west abutment and the lower part of the foundation of the Los Angeles Dam crest. PGA values were recorded at the right abutment and foundation levels as 0.33 g and 0.32 g, respectively. Longitudinal cracks were observed in the out-of-service Lower and Upper San Fernando Dams as a result of this earthquake. In addition, an opening between the Pacoima Dam concrete thrust block and the left abutment has been formed. This gap is approximately 2 inches. This gap is caused by the movement of the thrust block relative to the dam crest, and it is half an inch in size [12]. 1988 Chiba-ken Toho-oki Earthquake ($M_w=6.7$) caused minor damage to the Nagara Dam. Maximum acceleration (downstream) was recorded as 369 gal at the crest and 262 gal at the base [13]. The Shapai Dam, a Roller Compacted Concrete (RCC) arch dam located in China, sustained no damage during the Wenchuan earthquake. The Rapel arch dam is a double-curved dam that was exposed to the Santiago earthquake (03.03.1985). The earthquake's distance from the dam was

approximately 92 km, and its depth was 33 km. Measured accelerations were 0.31 g in the transverse direction of the canyon, 0.11 g in the vertical direction, and 0.14 g upstream and downstream. The dam body remained undamaged. Cracks have formed in the spillway walls, and leakage has been observed in the right spillway section. However, the water intake tower has cracked and separated at the top. This dam was affected by the Maule earthquake ($M_w = 8.8$) that hit on 27 February 2010. The dam, which has a full reservoir, is located approximately 232 km from the earthquake's epicenter. The acceleration measured at the dam is 0.21g. Cracks have appeared in the concrete lining sections at the crest of the dam. A 0.5 mm uplift was generated in the joints between the arch block and the adjacent block near the "Nido de Aquila" fault. While the leakage rate on the right abutment was normally 3.4 gal/s, it increased to 10.6 gal/s [14].

Okur et al. [15] evaluated in the seasonal frequency behaviour of Deriner Dam using artificial neural networks. Considering 14 months of monitoring data, it was assessed the effects of temperature and reservoir filling levels on frequency were assessed. Frequency estimation based on hydrostatic load and temperature variation was successfully achieved using an artificial neural network regression model. It was evaluated that the dam's behaviour depends on environmental changes. Okur et al. [16] investigated the behaviour of Yusufeli arch dam by utilizing artificial neural networks and Structural Health Monitoring data. It was demonstrated the effects of temperature and hydrostatic load on the dynamic behaviour of the dam were demonstrated. Okur [17] investigated the damping behaviour of Yusufeli Dam during water impoundment by considering different earthquake records. It was examined the effects of reservoir water level on damping behaviour were examined. Liang et al. [18] investigated the effects of ground motion selection and dynamic analysis methods on arch dams. Zhang et al. [19] examined arch dams and investigated the effects of outlet structures on arch dams. Gorai and Maity [20] carried out studies by obtaining fragility curves for concrete gravity dams considering synthetic near-fault movements. Ashna et al. [21] performed an incremental dynamic analysis considering a gravity dam structure. During the dynamic analyses, both the main earthquake and aftershocks were taken into account. The results indicate that aftershocks influence fragility. Cavuslu [22] conducted the seismic analysis of Ermenek arch dam by considering the different water levels of the reservoir. Cavuslu and Dagli [23] applied the various ground motions of the Kahramanmaras earthquake to Ermenek Dam and determined that plastic damage appeared around the dam gallery and that gallery openings had an important effect on damage formation. Khalid et al. [24] used intensity measures to determine the behaviour of concrete-faced rockfill dams under seismic effects. According to the results obtained, it was shown that the vector fragility surfaces are more effective than traditional scalar fragility curves in determining dam damage. Xu et al. [25] determined the seismic performance of

concrete-faced rockfill dams using the incremental dynamic analysis method and performed fragility analyses. Liang et al. [26] conducted a fragility analysis of an arch dam. It was determined that fragility analyses are important in the probabilistic assessment of a system's seismic performance. Wang et al. [27] conducted nonlinear damage analyses considering the Dagangshan Dam. It was evaluated the results of fragility analyses performed using IDA were evaluated. Çarhoğlu [28] performed seismic analyses of 8 arch dams located in Turkey and presented a reinforcement proposal. Korkmaz [29] conducted probabilistic analyses of arch dams in their study.

This study considers the Karakaya Dam, which is an arch dam, and is based on the model and analysis results obtained from studies published previously [28-29]. The aim of this research is to examine the effect of seismic motion on the response of Karakaya Dam by taking different ground motion records into consideration. According to the research conclusions, it was revealed that changes in the features of earthquakes have an important effect on the seismic behaviour of the dam. By performing Power Spectrum Analyses, the frequency content of each earthquake used in the seismic analysis was considered. The relationship between the dominant frequency of ground motion and the natural frequency of the dam, that is to say, the dam-seismic activity-frequency relationship, was determined. In addition, spectral acceleration values were determined to compare the natural period of the structure with the dominant period of seismic motion. Structural responses were evaluated based on spectral acceleration values. The relationship between structural responses and energy density was investigated by determining the Arias intensity values of seismic motions.

2. Numerical modelling of Karakaya Dam

To evaluate the behaviour of the dam body under the effects of seismic loading, it is necessary to perform seismic analysis. To that end, in this study, Karakaya Dam located in Diyarbakir province of Turkey is adopted for seismic analysis. The height from the foundation of the dam to the thalweg is 173 m and 158 m, respectively. The crest elevation is 698 m, the body volume is 2.000.103 m³, the crest length is 462 m, and the crest width is 12 m [30]. The dam body is made of C 30 concrete, with an elastic modulus of 32 GPa, a Poisson ratio of 0.2, and a unit weight of 24 KN/m³. Numerical modeling was performed using the finite element method with SAP 2000 software [31]. The finite element model of Karakaya Dam is presented in Fig. 1. The soil is assumed to be fixed support. The finite element model of the dam was created using three-dimensional solid elements. Solid elements generally have 8 nodes, and the structure consists of 4466 solid elements and 6075 points. Considering dam-reservoir interaction is quite significant for determining the behaviour of dams under seismic loads.

There are different methods used for dam-reservoir interaction. These methods are the Eulerian approach, Lagrangian approach, and Westergaard approach [32,33]. The hydrodynamic pressure of dam water is modeled by Westergaard's added mass approach [34]. According to this approach, water pressure is represented as added mass. Furthermore, the reservoir eigenfrequency and the impact of water compressibility are not considered [34;35]. The Westergaard approach assumes that the dam is rigid, that no fluid surface waves are formed, and that the water is incompressible. However, it was assumed that the reservoir is infinitely long, the upstream surface is vertical, and the reservoir length extends infinitely in the upstream direction. Hydrodynamic pressure distribution is considered as a mass distribution [33,34]. The formula related to the added mass approach is given in Eq. (1) [33,34,36]. Eq. (2) contains Westergaard's hydrodynamic pressure formula.

$$m(z) = \frac{7}{8} \frac{w}{g} \sqrt{Hz} \quad (1)$$

$$P(z) = \frac{7}{8} C \sqrt{Hz} \quad (2)$$

where m is the added mass; w is the density of water; H is the water depth; P is the hydrodynamic pressure induced in the course of an earthquake; C is the ratio of earthquake acceleration to gravitational acceleration [34,36]. In this study, Westergaard's added mass method was applied to the system as the water load.

While performing the analysis, Karakaya Dam is assumed to be exposed to different ground motions. The time history analysis method is utilized during seismic analysis. The acceleration-time records of earthquake loads were applied at the dam base in the course of the seismic analysis. To investigate the effect of the different earthquake characteristics on the seismic behaviour of the dam, 6 earthquake records with different properties were taken into consideration.

3. Seismic load selection

There are significant differences between near- and far-ground movements. In near-ground motions, the fracture mechanism depends on the displacement and slip direction taking place in the field. During seismic activity, situations such as forward movement, backward movement, and neutral movement can arise [37]. Unlike distant fault earthquakes, it exhibits characteristics such as forward-directivity and fling-step. Due to forward-directionality, large velocity pulses that change direction can be generated along the normal fault line. [38]. These ground motions have characteristics such as long-period components, long wave period, impulse-type motion, a high ratio of peak ground velocity to peak ground acceleration, and permanent displacement [39].

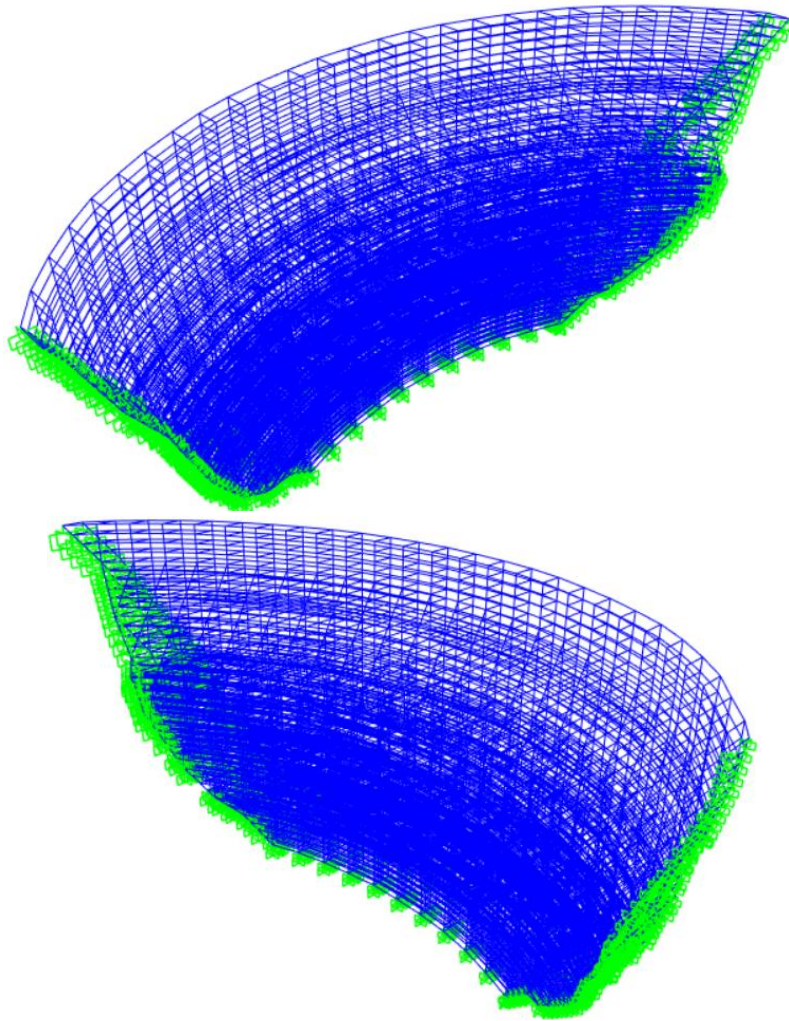


Fig. 1. The view of Karakaya Dam

Damage to structures caused by strong ground motions cannot be explained solely by high ground acceleration; high spectral acceleration values also play a role. However, the response spectrum alone cannot explain it. Although high spectral amplitudes were obtained in the Parkfield and El Centro earthquakes, no significant structural damage was observed at the Pacoima Dam [40]. When performing seismic analyses, intensity parameters such as effective ground acceleration (PGA), spectral acceleration, and Arias density can be used.

In this study, three different ground motions were applied to the Karakaya Dam. These earthquakes have different PGA (peak ground acceleration), focal depth, ground velocity, and frequency properties. The characteristics of seismic records utilized in the analyses are shown in Table 1. Figs. 2 and 3 show the time-dependent acceleration and velocity values of these ground motions. Using the selected ground motion records, Power Spectrum Analysis, Response Spectrum Analysis, pulse, and Arias intensity features were determined with Seismosignal software, and the drawings in this study were done using the MATLAB program. [42;43].

In the analyses, Borrego Mtn, Loma Prieta, Santa Barbara, N. Palm Springs, Whittier Narrows, and Kocaeli earthquakes were used. The record names of the ground motions are A-

PEL090, CLS000, SBA222, FVR045, ALH180, SKR090, respectively. Kocaeli earthquake struck on 17 August 1999, with a magnitude of 7.4. The effective ground acceleration was 0.376g. New Zealand Palm Springs earthquake, which hit on 8 July 1986, had an effective ground velocity of 0.129g. Loma Prieta earthquake hit on 18 October 1989, with a magnitude of 7.1 and a PGA value of 0.6437g. The values of the effective ground acceleration of the Borrego Mtn., Santa Barbara, and Whittier Narrows earthquakes are 0.012g, 0.203g, and 0.333g, respectively [41]. The time history analysis method was used when performing seismic analyses. Time intervals, total duration, and the number of each earthquake were used during the analyses.

Table 2 shows the PGV/PGA ratios for all earthquake records. This ratio demonstrates the relationship between maximum ground velocity and maximum ground acceleration, providing information about the characteristic features of the seismic events. The pulsed or non-pulsed conditions of the ground motions were determined using the Seismosignal program. As a result of pulse analyses, the Borrego Mtn and Loma Prieta earthquakes were identified to be non-pulsed, while the Palm Springs, Whittier Narrows, and Kocaeli earthquakes were revealed to be pulsed earthquakes.

1999 Kocaeli earthquake, with a magnitude of 7.4, was one of the major earthquakes that caused destructive effects and resulted in loss of life and property. The area around the Gulf of Izmit and the Sea of Marmara, where the earthquake hit, is a region with a high concentration of industrial facilities. These industrial facilities extend as far as Adapazarı. This earthquake caused extensive damage to numerous industrial facilities. Significant damages developed at the Tüpras oil refinery located near the Gulf. The damage at the Tüpras refinery includes crude oil processing units, cooling towers, port facilities, and storage tanks. The damage was caused by fires that broke out during the earthquake. One

of the cooling towers in the plant is reinforced concrete; three of the towers are wooden, and there was no significant damage to the reinforced concrete cooling tower. One of the wooden cooling towers was destroyed during the earthquake, and one of the towers was burnt and the other slightly damaged. One of the wooden cooling towers collapsed during the earthquake, another burned, and another sustained minor damage. Some parts of the Petkim Petrochemical plant suffered extensive damage. A wooden cooling tower at this plant completely collapsed. The adjacent tower showed no damage [44].

Table 1. The ground motion records used in the analysis [41]

Earthquake Number	Earthquake Name	Record Name	Year	Magnitude	PGA (g)	Focus Depth (km)	Type
EQ 1	Borrego Mtn	A-PEL090	09/04/1968	6.8	0.012	217.4	Strike-slip fault
EQ 2	Loma Prieta	CLS000	18/10/1989	7.1	0.6437	5.1	Reverse oblique slip fault
EQ 3	Santa Barbara	SBA222	13/08/1978	7.2	0.203	14	Reverse oblique slip fault
EQ 4	N. Palm Springs	FVR045	08/07/1986	6.0	0.129	13	Reverse oblique slip fault
EQ 5	Whittier Narrows	ALH180	10/01/1987	6.0	0.333	13.2	Reverse oblique slip fault
EQ 6	Kocaeli	SKR090	17/08/1999	7.4	0.376	3.1	Strike-slip fault

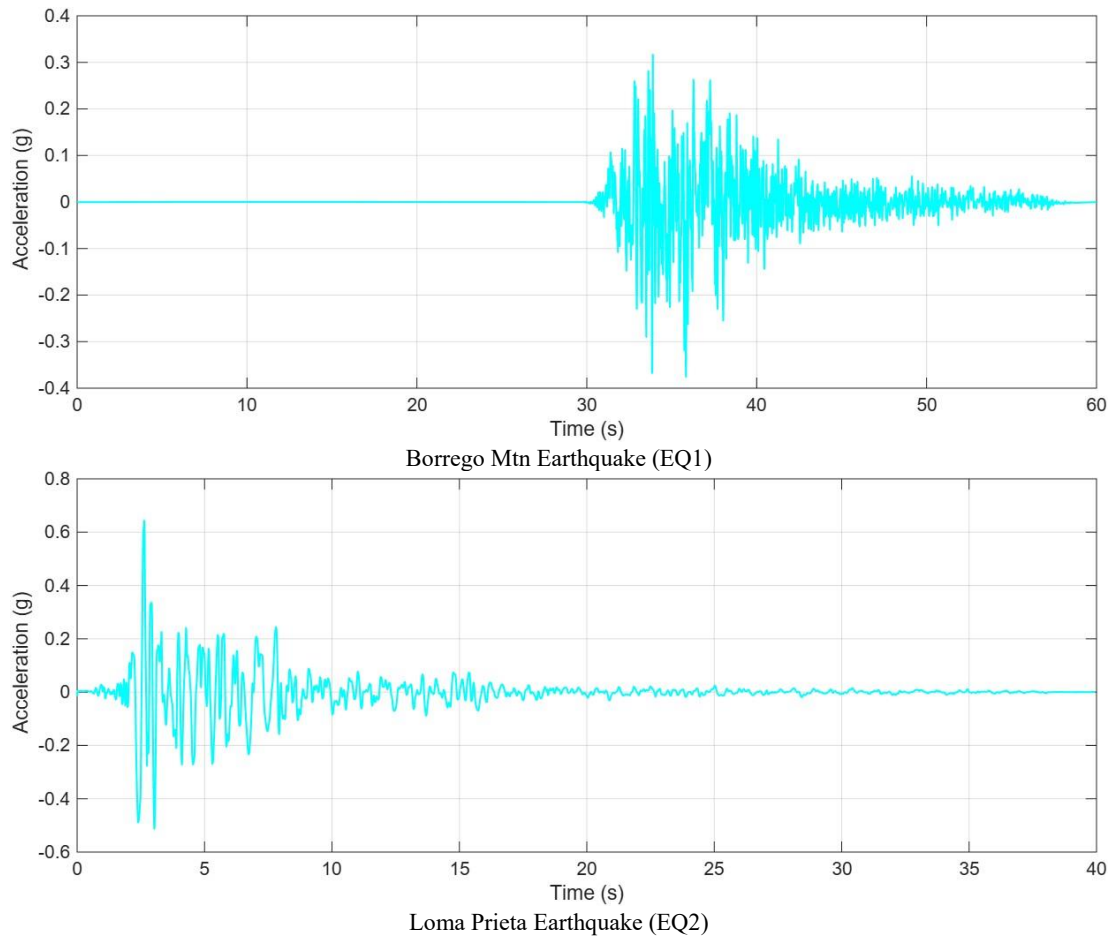


Fig. 2. Time-dependent acceleration values of earthquakes

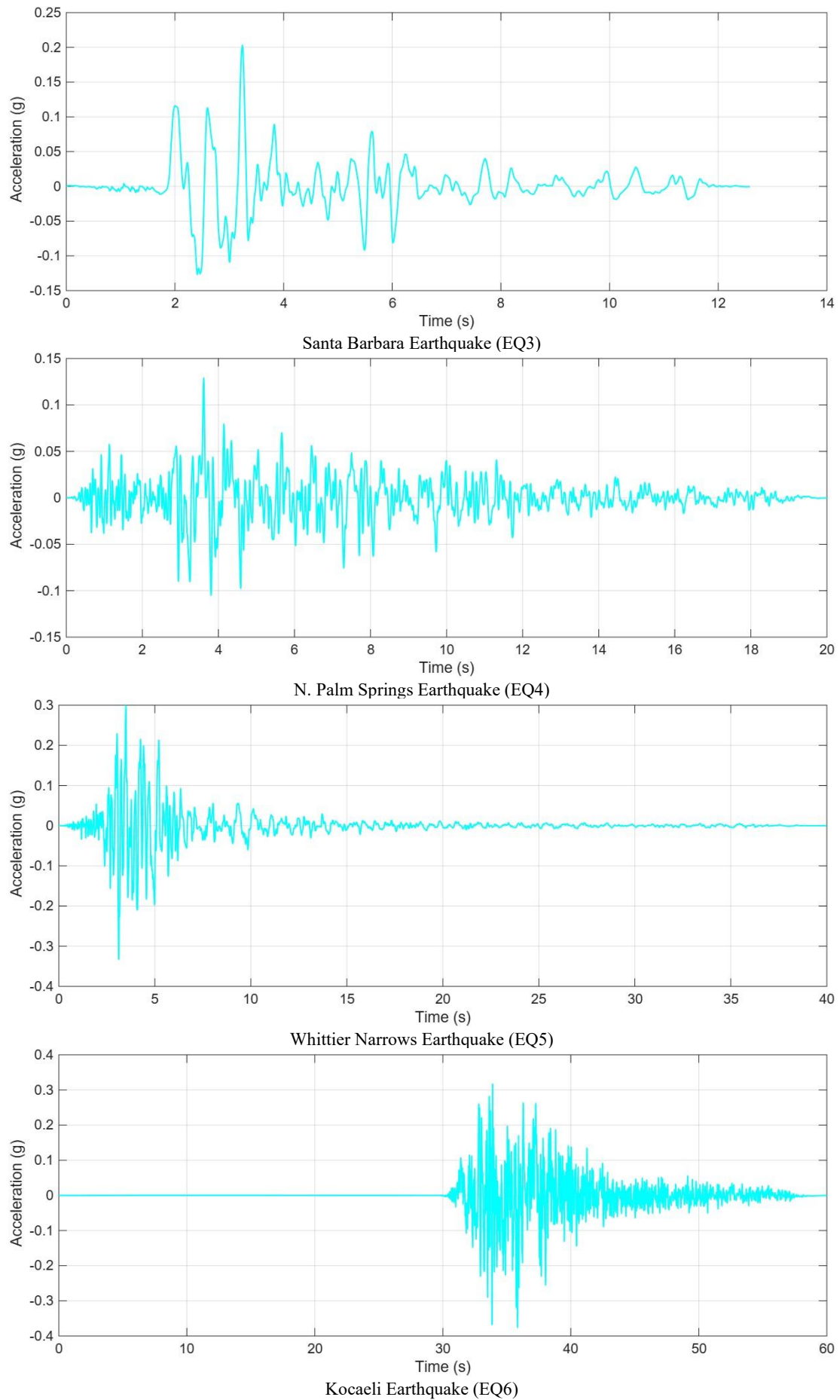


Fig. 2. Continued

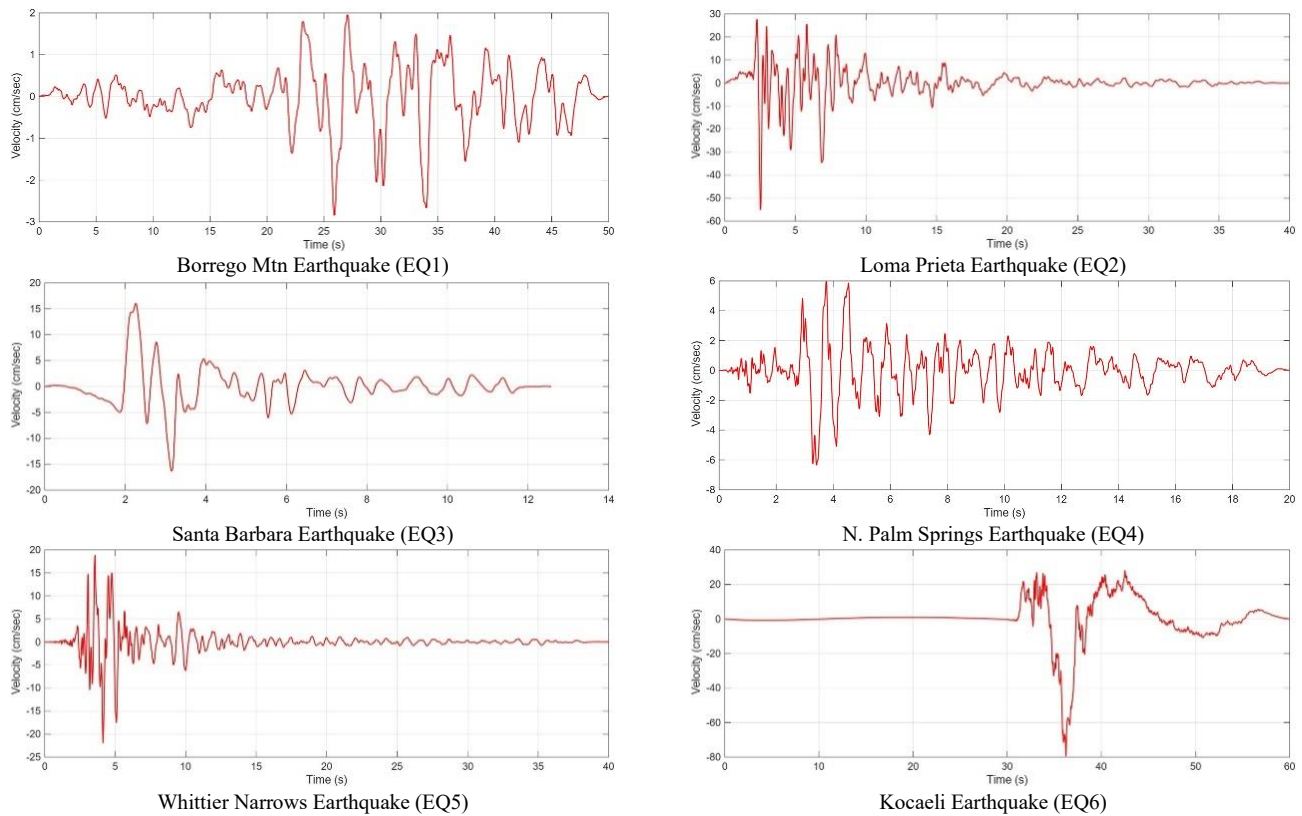


Fig. 3. Time-varying velocity values of seismic motions

Table 2. The properties of pulse or non-pulse condition of earthquakes

Earthquake Number	Earthquake Name	PGA (g)	PGV (cm/s)	PGV/PGA	Pulse Condition	Earthquake Number
EQ 1	Borrego Mtn	0.012	2.9	241.67	Ground motion without pulse	EQ 1
EQ 2	Loma Prieta	0.6437	55.2	85.75	Ground motion without pulse	EQ 2
EQ 3	Santa Barbara	0.203	16.3	80.30	-	EQ 3
EQ 4	N. Palm Springs	0.129	6.37	49.38	Ground motion with velocity pulse	EQ 4
EQ 5	Whittier Narrows	0.333	22	66.07	Ground motion with velocity pulse	EQ 5
EQ 6	Kocaeli	0.376	79.5	211.44	Ground motion with velocity pulse	EQ 6

The New Zealand Palm Springs earthquake (08.07.1986) had earthquake fault lines ranging from 5 km to 180 km, according to recordings from 46 USGS strong ground motion stations. 19 of these stations are at a distance of 50 km from the epicenter, and the values of ground acceleration range from 0.045 g-0.704 g (horizontal) to 0.038g- 0.778g (vertical) [45]. Loma Prieta earthquake (18.10.1989) was felt in Las Vegas, Reno, and Los Angeles, even though these areas were far from the epicenter. According to records from 38 USGS stations, the epicentral depths range from 27 to 115 km. The earthquake's epicenter was located 16 km northeast of Santa Cruz, California. Of the 38 stations where accelerometers are located, 13 are in buildings, 2 are at bridge piers, 2 are at dams, and 21 are ground stations. One of these USGS accelerometers is located at Anderson Dam. Anderson Dam is located in the east of Morgan Hill. Acceleration values of

0.39g and 0.38g were measured at the crest level of the dam, and 0.14g in the middle section. The maximum accelerations at the abutment, downstream, and toe sections of the dam were measured as 0.08g, 0.26g, and 0.23g, respectively [46].

4. The examination of results obtained from the analysis

4.1. Modal characteristics of Karakaya Dam

In this study, the Karakaya Dam was modeled in three dimensions using the finite element method. First, modal analyses were performed to assess the natural period values and mode shapes of the system. The mode shapes of Karakaya Dam are shown in Fig. 4. The first period value of the structure was obtained as 0.39 sec, the second period as 0.34 sec, the third period as 0.26 sec, and the fourth period as 0.22.

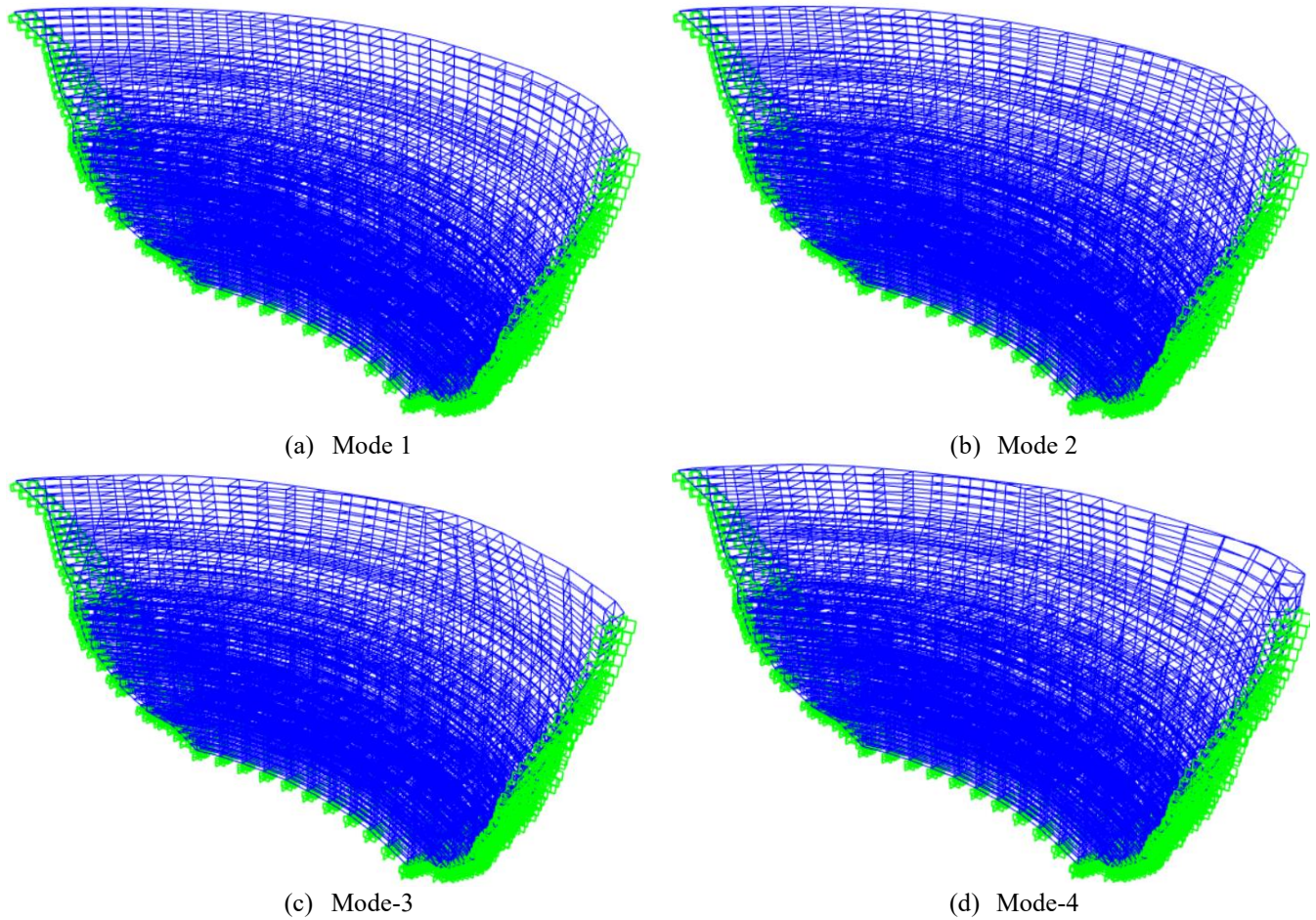


Fig. 4. Mode shapes of Karakaya Dam

4.2. Model validation

In this study, model validation was performed to demonstrate the reliability of the values obtained from numerical analyses. For this purpose, the natural frequency of Karakaya Dam was compared with studies in the literature.

The frequency comparison of this study with studies in the literature was presented in Table 3. Hariri-Ardebili et al. [47] found the frequency values of 6 different arch dams. The frequency values of the current study are identified to be close to the frequency values of the Karaj, Karun I, Karun III, and Luzzone Dams examined in this study [47]. The first natural frequency of Baixo Sabor Dam is 2.527 Hz and is the same as the frequency value of this study [48].

$$\omega = 23HSC + 1.23 \quad (3)$$

$$\omega = 23 \frac{H^2 \sqrt{L_{crest}}}{V_{Body} t_{ave}} + 1.23 \quad (4)$$

In addition, the formula is given in Eqs. (3) and (4), where H is the dam height, L is the crest length, V_{body} is the dam body volume, and t is the average thickness [47]. HSC is the Hariri Shape Coefficient. The frequency value of Karakaya Dam was determined using this formula. The frequency value computed from the analytical formula is 1.846 Hz, while the natural frequency of Karakaya Dam modeled using the finite element method is 2.564 Hz.

The difference between these values is % 39, and considering that this difference stems from the geometry of the dam and the material properties, it can be concluded that the obtained frequency values of frequency are consistent [47].

4.3. Performing power spectrum analyses

In this study, Power Spectrum Analyses were performed to determine the energy distribution and frequency content of different ground motions. Seismic records in the time domain are transformed to the frequency domain by utilizing this method. Dominant frequencies of earthquakes can be computed using the power spectra of the ground motions.

Table 3. Comparison of the structure's frequency value with the frequency values of dams in the literature

Structure	Natural Frequency (Hz)
Present study	2.564
Karaj Dam [47]	2.286
Karun 1 Dam [47]	2.037
Karun III Dam [47]	2.411
Luzzone Dam [47]	2.423
Baixo Sabor arch dam [48]	2.527

The frequency contents of 6 different earthquakes derived from Power Spectrum analyses are shown in Fig. 5. It is evident that the frequency components of seismic events vary from each other. The dominant frequency of the Borrego Mtn earthquake was found to be the smallest (0.537 Hz); the dominant frequency values of Loma Prieta, Santa Barbara, N. Palm Springs, Whitter Narrows, and Kocaeli earthquakes were revealed to be 1.416 Hz, 1.660 Hz, 1.367 Hz, 4.199 Hz, and 3.125 Hz, respectively. The dominant frequency value of Karakaya Dam is 2.564 Hz, and this value does not coincide with the dominant frequency of the seismic ground movements. In other words, in the evaluation made in terms of frequencies, no frequency match was found for the earthquakes used in the analyses.

4.4. The spectral acceleration analysis

Acceleration response spectra were found to determine the period-dependent characteristics of 6 ground motions applied to Karakaya Dam. The damping ratio was taken as 5%. The resulting spectrum curves are shown in Fig. 6. Spectral curves were created for each earthquake and compared based on period values.

For Borrego Mtn, Loma Prieta, Santa Barbara, N. Palm Springs, Whitter Narrows, and Kocaeli earthquakes, the maximum spectral accelerations were determined as 0.04g,

2.18g, 0.54g, 0.34g, 1.27g, and 1.11g. The corresponding periods are 0.8 sec, 0.3 sec, 0.55 sec, 0.15 sec, 0.25 sec, and 0.15 sec. As a result of the modal analyses performed, the first natural vibration period of the structure was obtained as 0.39 sec. It is found that the natural vibration period of Karakaya Dam does not coincide with the dominant period values of the seismic movements.

The variation between the values of spectral acceleration-stress-displacement is shown in Fig. 7. The spectral acceleration value of the Loma Prieta earthquake is 2.17g; the largest displacement and stress values for both the empty and full states of the dam were calculated for these ground movements. The smallest values of spectral acceleration value was obtained, 0.04g, in the Borrego Mtn earthquake, and the smallest structural responses for empty and full reservoir conditions of the dam were obtained in this seismic motion. The values of spectral acceleration were determined as 0.536g, 0.337g, 1.27g, and 1.11g for Santa Barbara, N. Palm Springs, Whitter Narrows, and Kocaeli earthquakes, respectively. The displacement values obtained in the empty reservoir situation were obtained as 33.32 mm, 25.73 mm, 68.96 mm, and 47.54 mm, respectively. For the full reservoir condition, it was obtained as 57.46 mm, 47.60 mm, 81.96 mm, and 71.16 mm, respectively.

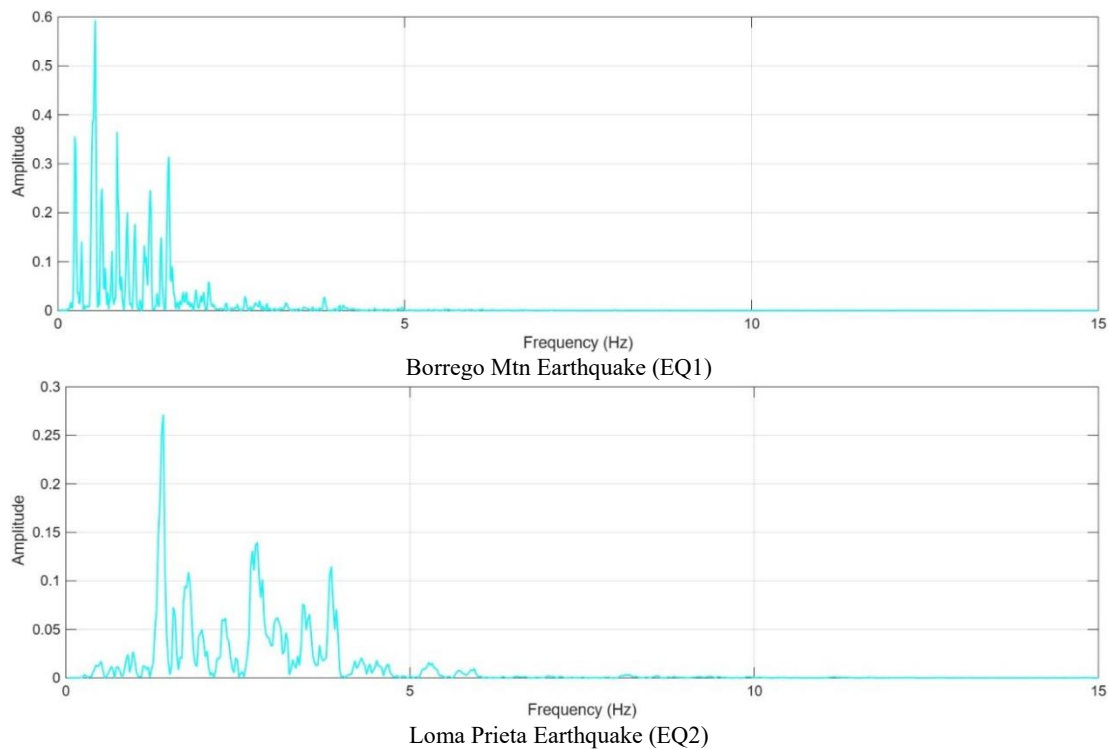


Fig. 5. Frequency spectra obtained from power spectrum analyses

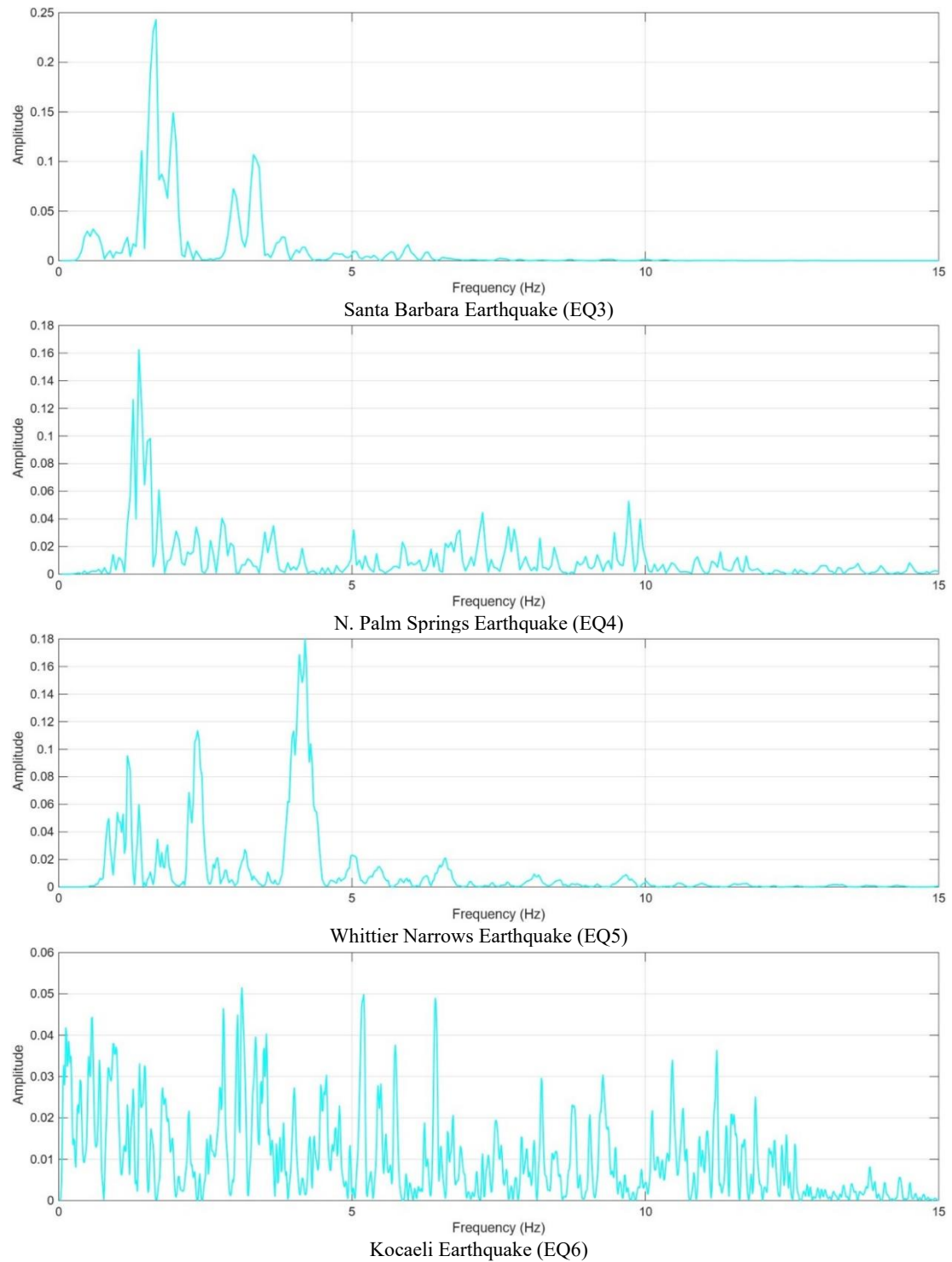


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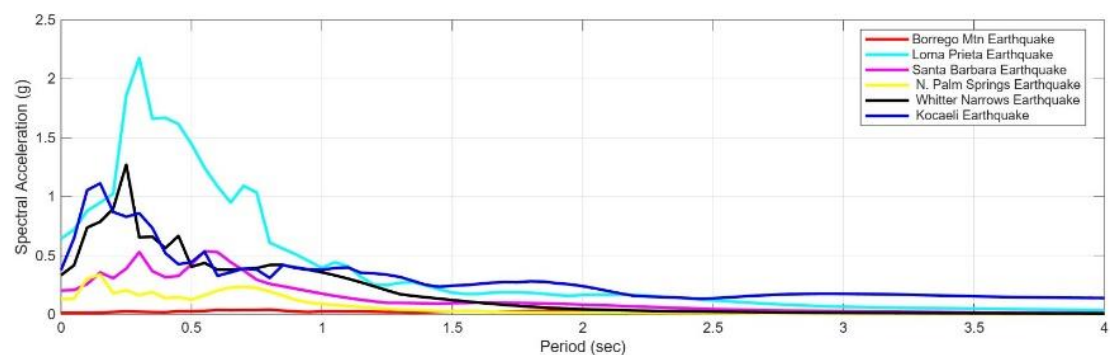


Fig. 6. The relationship between spectral acceleration-period values of seismic motions used in the analyses

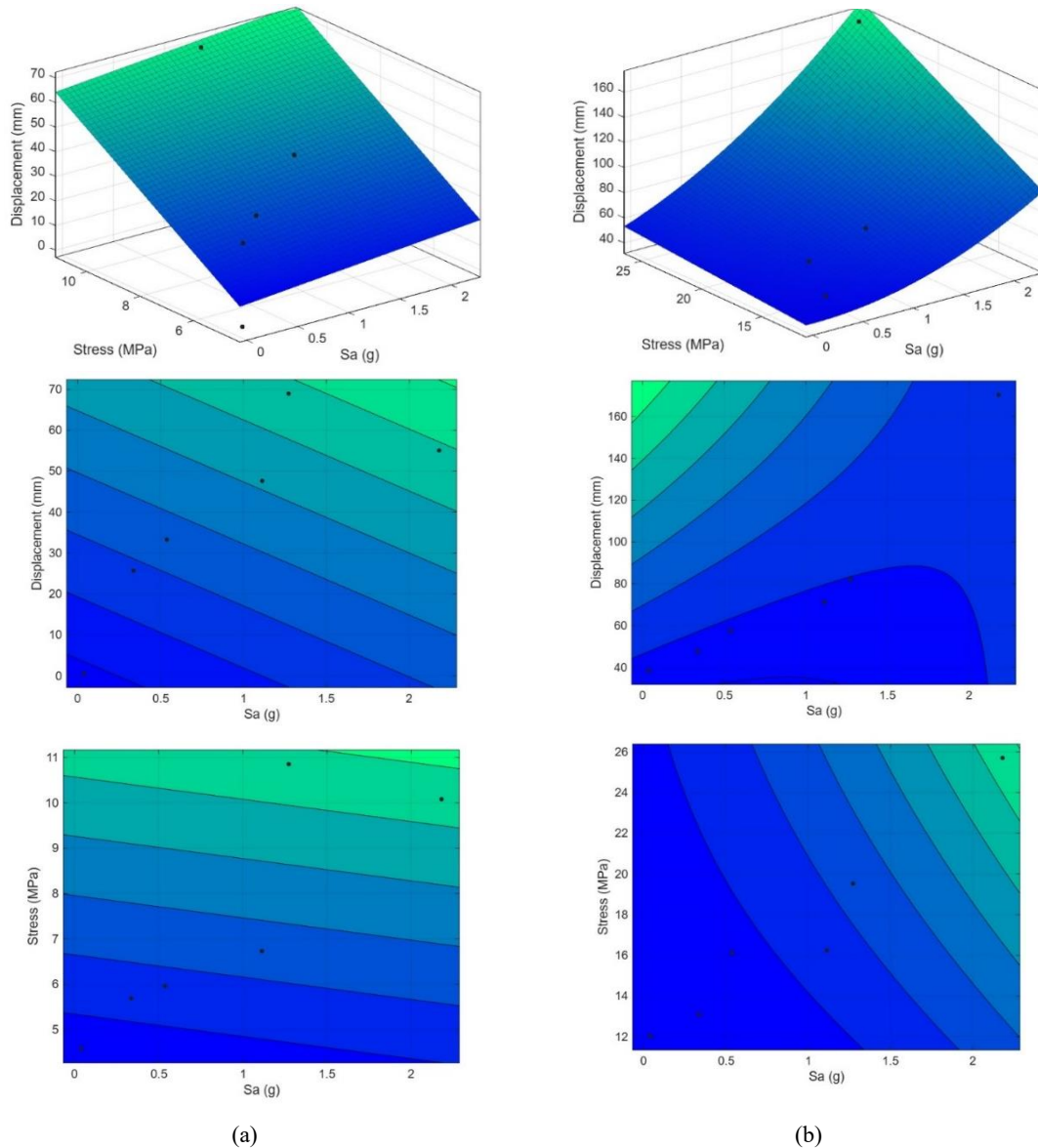


Fig. 7. The relationship between the displacement-stress-spectral acceleration: a) Empty condition, b) Full condition

4.5. The investigation of seismic responses of Karakaya Dam

Seismic records with different characteristics were considered and applied to the system, and analyses were performed using the time domain method. 6 seismic motion records with different characteristics were applied to the dam, and displacement and stress values were obtained for both empty and full states of the dam reservoir.

The relationship between the values of displacement, stress, and effective ground motion obtained as a result of applying different seismic loads to Karakaya Dam is shown in Fig. 8. The greatest displacement values arose at the dam crest level. The maximum effective ground acceleration value of the seismic inputs used in the analyses is recorded as 0.6437g in the Loma Prieta earthquake (EQ2). The magnitude of this earthquake is 6.93. The calculated values of displacement with the application of this earthquake to

Karakaya Dam are 55.11 mm and 170.47 mm for empty and full reservoir cases, respectively. The stress values obtained for this seismic loading in both empty and filled reservoir conditions are 10.07 MPa and 25.71 MPa, respectively. The smallest displacement and stress values were obtained by applying the Borrego Mtn (EQ1) earthquake to the dam for empty and full reservoir cases. The effective ground acceleration value of this earthquake is 0.012g. For this earthquake, the displacement and stress values obtained in the empty state were determined as 0.55 mm and 4.58 MPa, respectively, while the values of displacement and stress obtained in the filled condition were obtained as 38.34 mm and 12.03 MPa, respectively. Structural responses obtained by applying other seismic records to the system also vary depending on the characteristic features of the earthquake. In all earthquake conditions, it has been observed that the structural responses obtained when the dam reservoir is full are greater than those obtained when the reservoir is empty.

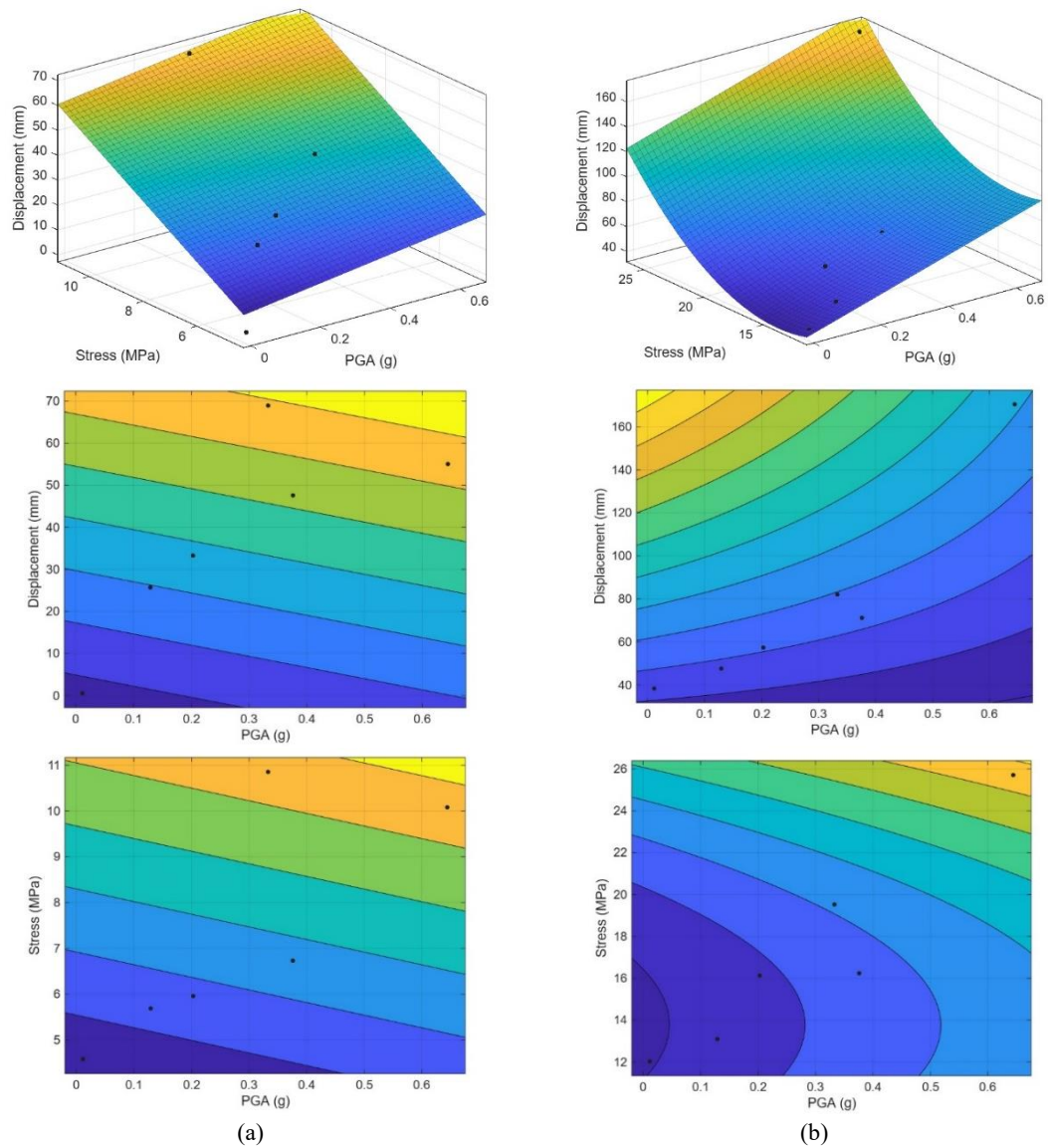


Fig. 8. The relationship of displacement -effective ground acceleration: a) Empty condition, b) Full condition

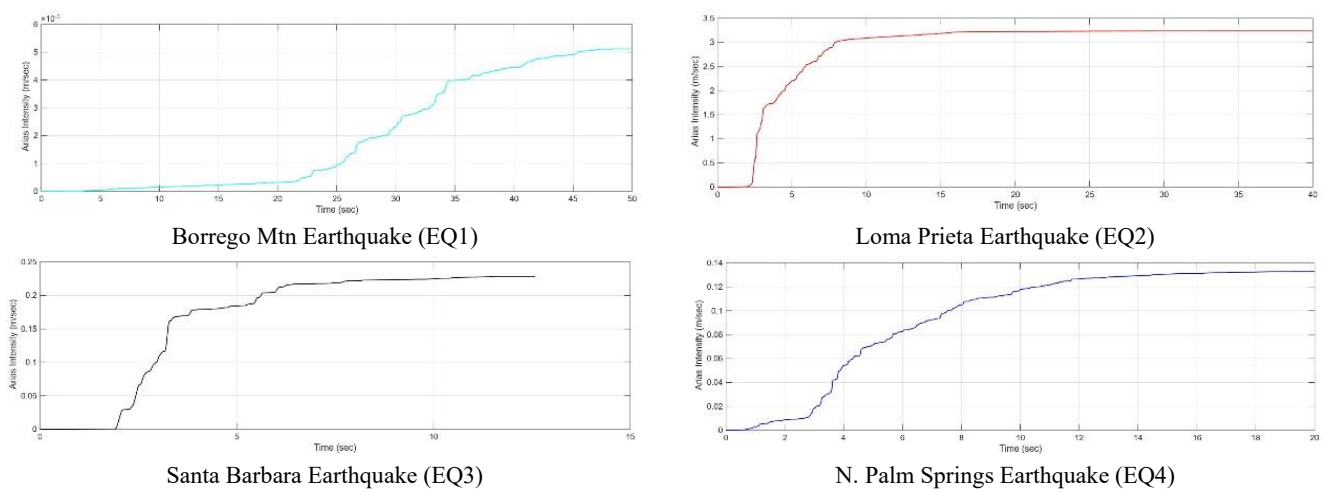
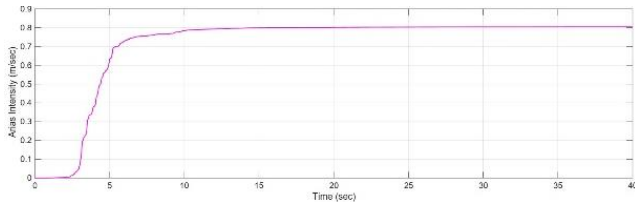
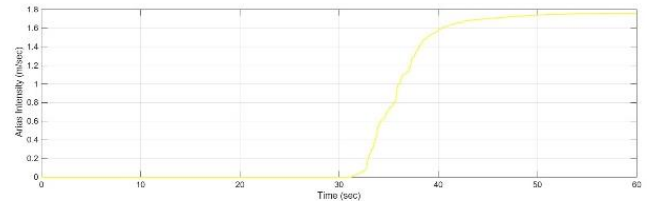


Fig. 9. The time-dependent Arias intensity values of ground motions



Whittier Narrows Earthquake (EQ5)



Kocaeli Earthquake (EQ6)

Fig. 9. Continued

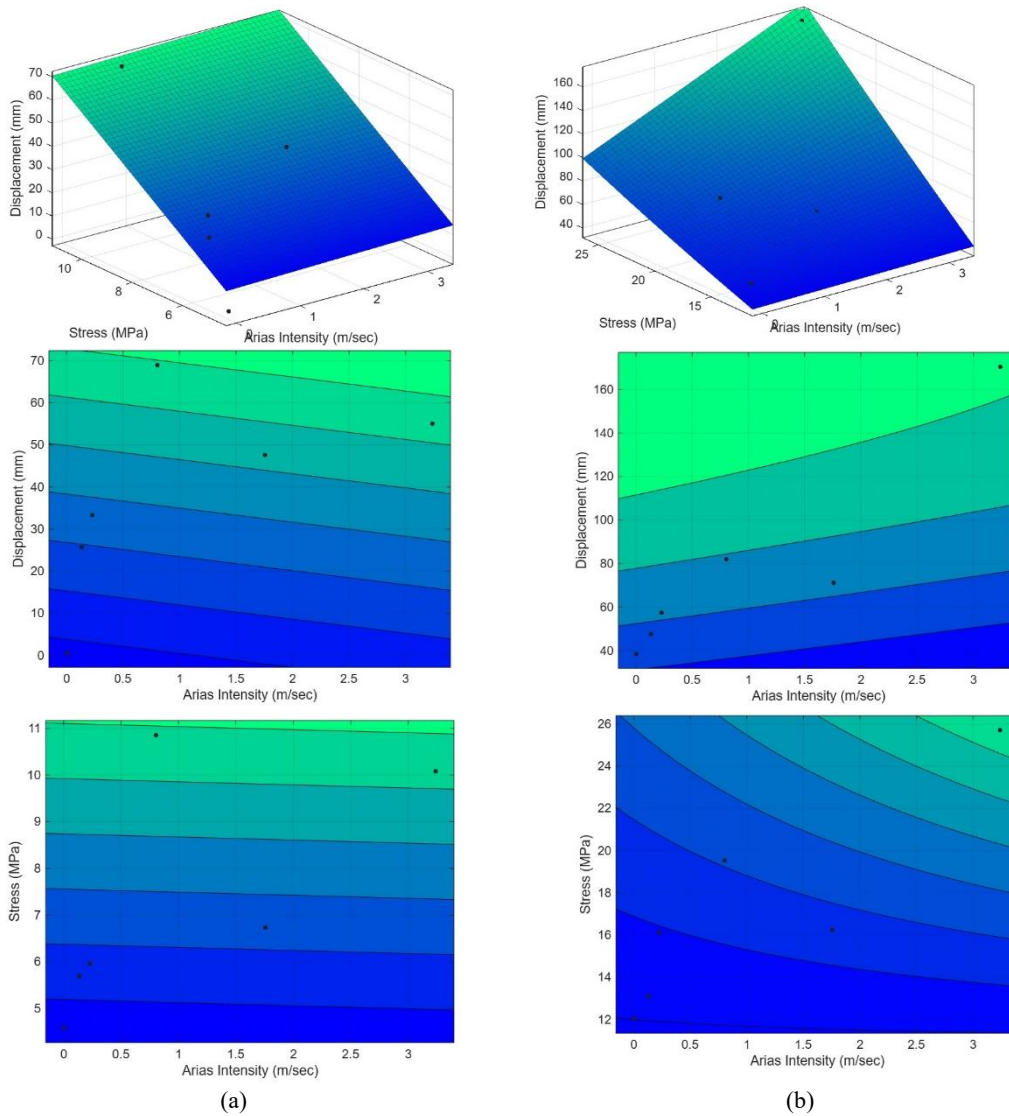


Fig. 10. The comparison of displacement-stress-Arias intensity: a) Empty condition, b) Full condition

Table 4. The values of Arias intensity and significant duration of earthquakes used in the analysis

Earthquake Number	Earthquake Name	Significant Duration (sec)	Arias Intensity (m/sec)
EQ 1	Borrego Mtn	26.795	0.00512
EQ 2	Loma Prieta	6.880	3.23682
EQ 3	Santa Barbara	4.640	0.22866
EQ 4	N. Palm Springs	10.265	0.1328
EQ 5	Whittier Narrows	5.265	0.80498
EQ 6	Kocaeli	9.860	1.7582

In this study, the values of Arias intensity and significant duration are calculated in order to investigate the variation between earthquake energy intensity and structural responses. The time-dependent change of Arias intensity values is shown in Fig. 9, and the values of maximum Arias intensity and significant durations are shown in Table 4. Significant Duration is the time between 5% and 95% of the Arias intensity value, and is determined as 26.795 sec, 6.880 sec, 4.640 sec, 10.265 sec, 5.265 sec, 9.860 sec, respectively, for Borrego Mtn, Loma Prieta, Santa Barbara, N. Palm Springs, Whittier Narrows and Kocaeli earthquakes. This duration

indicates the time of strong ground motion and shows that the structure was exposed to seismic loading for a longer period.

In Fig. 10, the Arias intensity of the Loma Prieta earthquake is the highest, with a value of 3.235 m/sec, and the significant duration is 6.88 sec. It was found that the values of displacement and stress obtained in this ground motion when the dam was full were greater than those of other earthquakes. The earthquake with the smallest Arias intensity value is the Borrego Mtn earthquake, and this value is 0.00512 m/sec. The values of smallest displacement and stress were obtained in this earthquake. The change in structural responses generally does not vary linearly depending on the magnitude of the Arias intensity value. The variation in structural responses depends not only on the energy content but also on the characteristic features and frequency content of the ground movements.

5. Conclusions

In this study, three time-dependent ground motions with different characteristics were applied to Karakaya Dam. The analysis results performed using the time-domain method revealed structural responses. However, Power Spectrum analyses were performed considering the ground motion records used in the analyses.

1. According to Power Spectrum analyses, the frequency content of each earthquake was found to differ depending on the characteristics of the earthquakes. It was determined that the dominant frequency values obtained for each earthquake did not coincide with the natural frequency value of Karakaya Dam. Consequently, it was observed that frequency matching did not occur for these ground motions.
2. Structural responses vary depending on the frequency content of earthquakes.
3. For all seismic movements, the highest spectral acceleration value was observed to take place within a period range different from the structure's natural vibration period. That is to say, it was concluded that the maximum spectral demand value of the seismic motion does not occur within the dam's natural vibration period.
4. The structural responses of Karakaya dam vary depending on the characteristic features of the earthquakes, such as peak ground acceleration, ground velocity, and magnitude.
5. In earthquake engineering applications, considering characteristics such as the properties, frequency content, and energy density of ground movements is crucial in terms of determining the structural behaviour of the dam.
6. Using earthquake records with different characteristics, rather than a single record, to determine structural safety is important for engineering applications, as it allows for the identification of how structures will behave under the influence of earthquakes with varying frequencies.

Declarations

Conflict of interests

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Author contributions

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Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

The author(s) confirm the author(s) did not use any AI tools in the preparation of this work/research/study.

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