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Research Article

Investigation of the behavior of Gezende Dam under seismic excitation

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ABSTRACT

Since structural failure can lead to major loss of life and severe economic damage, evaluating arch dams under strong ground motions is essential. In this study, so as to evaluate the behaviour of the system against strong ground motions, the effect of seismic parameters is examined in terms of determining structural safety. In order to simulate the behavior of arch dams under the seismic excitations, Gezende Dam in Türkiye was selected as the case study. Five earthquake ground-motion records were taken into account to evaluate the seismic response. As a result of the analysis, maximum displacement and stress values were determined through the numerical simulations. The frequency contents of the ground motions were defined by Fast Fourier Transform, while the structural demand was evaluated through spectral acceleration. Spectral Analysis, Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) analyses were performed for all the earthquake records. The structural behaviour was comparatively examined by considering the frequency content and spectral acceleration values of seismic motions. The findings obtained highlighted that the dam-reservoir system ought to be considered in the assessment of the performance of the arch dams. Furthermore, it was determined that earthquake characteristics affect the stress and the displacement distributions of arch dams. The results obtained are of great significance for engineering applications in the seismic evaluation of arch dams that exist and the ones that might be constructed.

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1. Introduction

Arch dams are widely employed owing to their numerous advantages. To ensure the structural integrity of arch dams during construction, longitudinal and transverse joints are formed between dam blocks. To enhance impermeability, pressure grouting and other methods are applied, and thus the arc dam acts as a monolithic structure (Huang and Han 2023; Zeinizadeh et al. 2018). Arch dams that are not constructed as single monoliths contain discontinuities due to their construction joints. These expansion joints, which separate the cantilever blocks, also separate the dam body from the concrete

abutment. These contraction joints subjected to shear and tensile stresses act as planes of weakness (Zeinizadeh et al. 2018). As arch dams have thin cross-sections, gate chambers located within the body of the dam may not be supported completely, which results in downstream and upstream regions that demonstrate cantilever behaviour. The interfaces between the dam and the suspended segments play an important role in transferring the load. Hence, the structural response of the interfaces and their adjacent areas remarkably influence the functionality of the water discharge in the dam structure (Zhang et al. 2015). The abutment and the foundation systems of arch dams are highly complex due to geologi-

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cal situations. Therefore, large-scale excavation activities are necessary during the construction process (Zhao and Wu 2020).

The security and the performance of arch dams are determined by geological situations, seismic design effects and important water thrust. All these factors are of vital importance to preserve their structural stability against seismic loads (Liang et al. 2025). Arch dams are constructed to store water for energy production, irrigation, and flood control purposes. When an arch dam is damaged during seismic events, the release of a large amount of water from its reservoir can result in devastating loss of life and property (Jin et al. 2019). However, arch dams can be structured in areas with high seismicity. Thus, evaluating the seismic resistance of arch dams is of great significance owing to the damage resulting from the strong ground motion.

Ainono Dam was influenced by Akita-ken Nantobu earthquake. Makio Dam was slightly damaged during the Nagano-ken Seibu earthquake (Tani 2000). A large number of earth dams were damaged in China during Wenchuan earthquake and in Japan during the Hogo-Ken Nanbu earthquake (Jin and Lee 2024). Numerous dams in Türkiye were damaged during 2023 Kahramanmaraş earthquakes (Hariri-Ardebili and Tosun 2024).

Moghaddam et al. (2026) studied the damage evolution by conducting dynamic analysis of an arch dam. It was determined that close fault seismic records lead to greater structural reactions and damage than the distant fault. Guo et al. (2025) examined the breathing behavior of transverse joints of arch dams through dynamic analyses. The method proposed was applied to a high arch dam in southwestern China. By using this method, it was concluded that the maximum opening depth and duration that might occur in transverse joints during seismic activity could be predicted. Zhang et al. (2025a) evaluated the joint opening and damage conditions by examining the behavior of the GX arch dam with three different reservoir conditions under seismic loads. Zhang et al. (2025b) carried out the nonlinear dynamic analysis by taking different velocity pulse situations into account. Following the artificial simulation methods, the magnitude and duration of nearby fault movement were shown to have a significant impact on the dam's behavior. Li et al. (2024) examined three arch dams with varying degrees of symmetry, considering both extreme and normal load conditions. Since asymmetric foundations might lead to stress and deformation, strengthening measures were investigated. Wang et al. (2024) investigated the effects of near-fault ground motion records on the seismic performance of high arch dams. Yan et al. (2024) performed nonlinear dynamic analyses by considering a high arch dam. Yan et al. (2023) examined the sliding resistance of the foundation-arch dam system by considering uncertainties in the modeling parameters, the ground motions and their combined effects. The findings indicated that these uncertainties significantly affect the sliding resistance of the foundation-arc dam. Jin et al. (2023) performed the fragility analysis of arch dams. It was concluded that the demand level substantially influences the reliability of fragility curves and the effect of material uncertainties is limited. Zhuang et al. (2019) examined the development and the propagation of crack within gallery

structures of arch dams constructed in complex geological regions with high seismic activity, considering the effects of the high arch dams' self-weight and the condition of the reservoir filling. Jin et al. (2020) performed dynamic analyses of the Dagangshan Dam based on the acceleration response spectrum. Türkmen (2010) investigated water leaks and deformations in the energy tunnels of Gezende Dam. Korkmaz and Çarhoğlu (2018) performed a probabilistic seismic assessment of the eight existing arch dams in Türkiye. Çarhoğlu (2012) carried out dynamic analyses of arch dams in Türkiye and examined the effect of the strengthening method.

There are many arch dams in seismically active regions of Türkiye. This study examines the behaviour of Gezende Dam, an arch dam in Türkiye, under the influence of different earthquakes. The dam model examined is based on the models and their analyses from previously published studies (Çarhoğlu 2012; Korkmaz and Çarhoğlu 2018). In recent years, strong ground motions such as Kahramanmaraş (Pazarcik), Kahramanmaraş (Elbistan), Kocaeli (1999), and İzmir (2020) earthquakes occurred. During earthquakes, significant structural damages may occur in arch dams. For this reason, seismic performance assessment is of vital importance in terms of earthquake engineering. Determining the behaviour of the Gezende Dam, located on an active earthquake zone in Türkiye under different seismic characteristics is crucial. PGA, PGV, focus depth and frequency content characteristics of earthquakes significantly affect the dynamic behavior of the structure. Signal and modal analyses provide information about the resonance potential of the structure. Determining the performance of the structure during earthquakes with similar PGA and frequency content is of great importance for dam structures. The main purpose of this study is to evaluate structural performance by considering real earthquake data. However, Investigating the effects of earthquakes with different frequency characteristics on the behaviour of arch dams under seismic loads is of great significance. For this reason, the ground motion records with different frequency content were used to evaluate the seismic behavior of Gezende Dam. The displacement and stress values that were obtained by applying time history method to the dam structure were comparatively investigated. Unlike previous studies; the effects of the frequency contents of earthquake records on the dynamic behaviour of Gezende Dam were assessed. The dam's resonance potential was determined by comparing the dam's natural frequency with the dominant frequency of each earthquake in the analyses.

2. Case Study: Gezende Dam

This study investigated the behavior of Gezende Dam, an arch dam with a height of 75 m from the base, under seismic loading. The dam has a double-curvature geometry. The dam was constructed in Mut district of Mersin province. The dam's volume at normal water level is 91.90 hm³, its body volume is 83,000 m³, and its reservoir area is 3.97 km². The dam's crest elevation is 335 m, its crest width is 7.5m, and its crest length is 120m. (DSI 2010). The concrete class of this arch dam is C30. The

elastic modulus, unit weight (KN/m^3), and poisson ratio of the dam were taken as 32 GPa, 24 KN/m^3 , and 0.2 respectively. The material model is assumed to be linear. The dam was modelled as eight-node solid (brick) elements by using SAP 2000 V14. finite element software, and for the seismic safety assessment of Gezende Dam, a time-history analysis method was used (Wilson 1997). The finite element model of the dam structure consists of 295 solids and 649 points. In the course of time history analysis; the time step was taken to be the same as the sampling interval (Δt) of each earthquake record. The earthquake excitation was applied to upstream–downstream direction (the normal direction to the dam crest). Only one component of the earthquake was applied to the system. Damping ratio of % 5 was assigned to the dam structure. The soil was not modelled in this study. The dam–foundation interface was assumed to be fixed. The finite element model of Gezende Dam as the case

study is shown in Fig. 1. During the analysis, the data of five strong ground motions were selected to examine the seismic performance of Gezende Dam. To determine the structural responses, the values of the displacement and stress were determined.

Reservoir was modelled by utilizing the Westergaard added mass approach (Westergaard 1933). Eqs. (1) and (2) show the water pressure acting on the dam surface and the added water mass. Here; P is the pressure acting on the dam surface, w is the unit weight of water, h is the reservoir height, and y is the water depth from the water surface (Westergaard 1933; Salamon 2018).

$$p = \frac{7}{8} w \alpha \sqrt{h(h-y)} \quad (1)$$

$$m = \frac{7}{8} w \sqrt{h(h-y)} \quad (2)$$

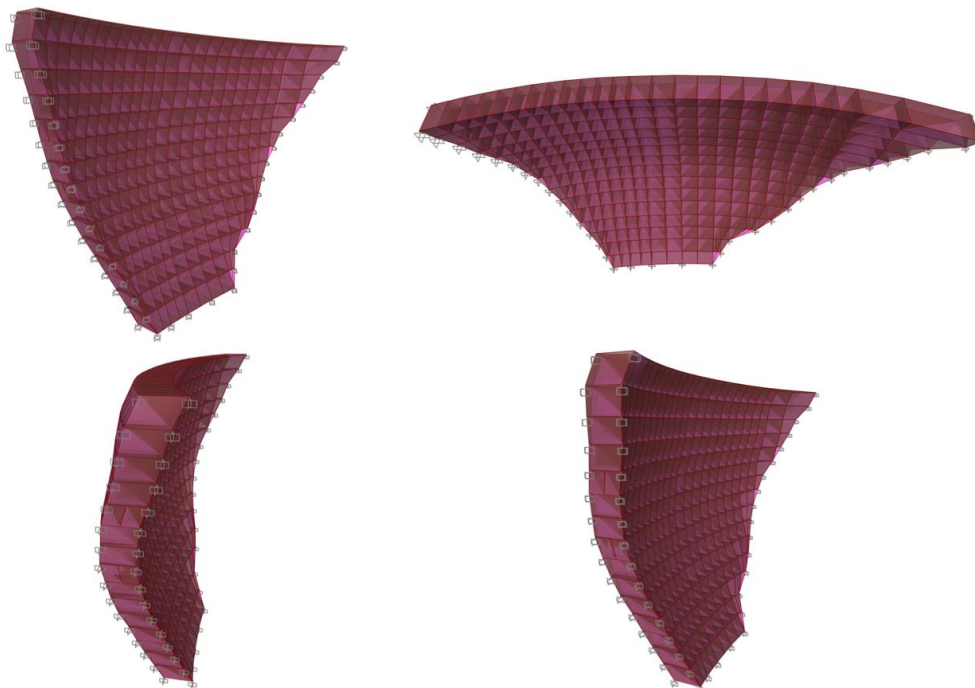


Fig. 1. View of Gezende Dam.

Earthquake records with different characteristics were selected to evaluate the structural behavior. The selected ground motions were determined to have different magnitudes, depths of focus and spectral contents. To determine the relationship between the structure's behavior under seismic loads and the dominant frequencies of earthquakes, recordings with different frequency contents were selected. No ground-motion scaling procedure was performed. Original ground motion records obtained from the PEER database were utilized in the time history analyses. No filtering has been applied to the earthquake records. The time dependent acceleration records obtained by using PEER data are shown in Fig. 2 (PEER 2010). The earthquake records used in the analyses are shown in Table 1 and these records were obtained from the PEER Ground Motion Database (PEER 2010; PEER 2026). The graphics were generated using MATLAB (MathWorks 2024).

The epicenter of the Coyote Lake earthquake ($M_w=5.74$, local magnitude of $M_L=5.9$), which occurred on August 6, 1979, was located on the Calaveras Fault, approximately 100 km southeast of San Francisco. The depth of the fracture surface varied between 4 km and 12 km and the length was 20 km. The breaking surface with such dimensions was rectangular (King et al. 1981). The seismic activity occurred in the form of right-lateral strike-slip faulting (Lee 1979). According to geodesic data, the right lateral shift was approximately 0.33 m. When geodesic data were examined, no prior signs of Coyote Lake earthquake had been seen before the earthquake (King et al. 1981). The spatial distribution of this earthquake is presented in Fig. 3 (USGS 2026). It is seen that the seismic shaking was concentrated along the fault and PGA values were increased in the sections close to the focus area.

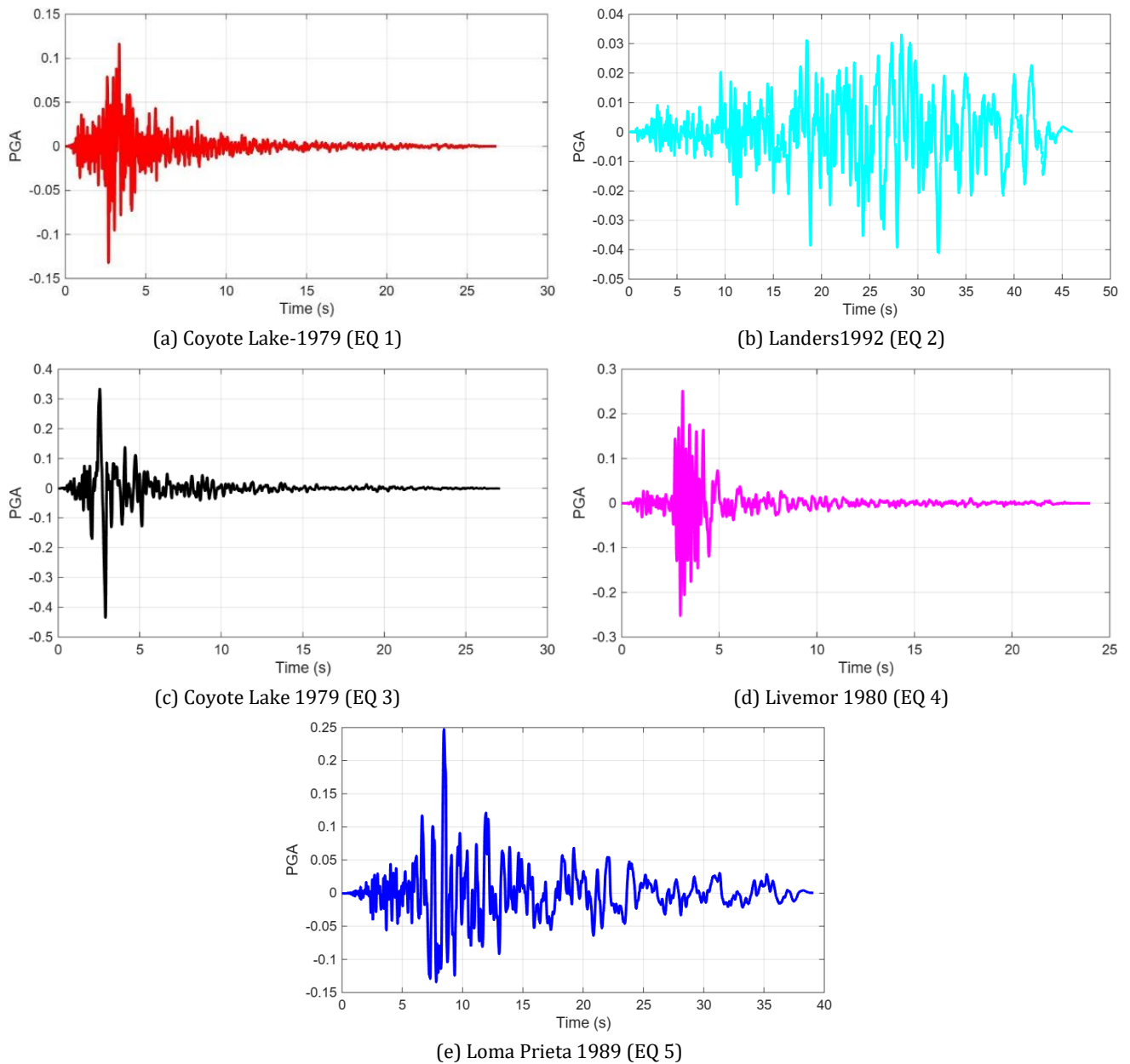


Fig. 2. Time-dependent variation of the earthquakes.

Table 1. Characteristics of the earthquakes used in the analyses.

Earthquake Number	Record Sequence Number	Earthquake Name	Date	Station Name	Magnitude (M_w)	Record Name	NEHRP Site Class (Based on V_{s30})	PGV (cm/s)	PGA (g)	Joyner-Boore Dist. (km)	Fault Type
1	146	Coyote Lake	06/08/1979	Gilroy Array #1	5.74	G01320	B	8.3	0.132	10.21	Strike-Slip
2	889	Landers	28/06/1992	San Gabriel - E Grand Ave	7.3	GRN180	C	14.1	0.041	141.92	Strike-Slip
3	150	Coyote Lake	06/08/1979	Gilroy Array #6	5.74	G06230	C	49.2	0.4339	0.42	Strike-Slip
4	222	Livermore	27/01/1980	Livermore - Morgan Terr Park	5.42	LM0355	C	9.8	0.252	7.94	Strike-Slip
5	777	Loma Prieta	18/10/1989	Hollister City Hall	6.93	HCH090	D	38.5	0.247	27.33	Reverse oblique-slip

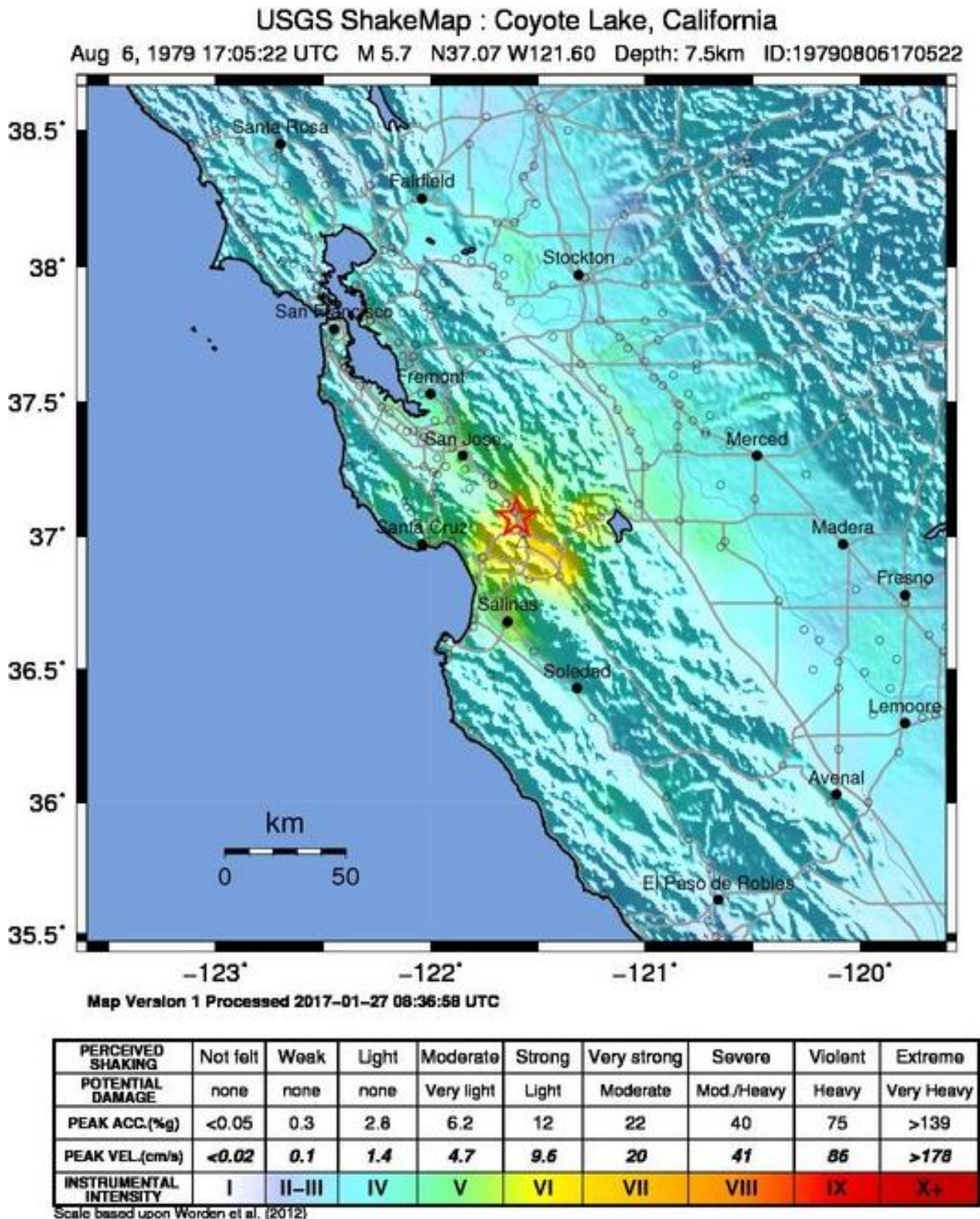


Fig. 3. Coyote Lake Earthquake map (USGS 2026).

3. Modal Analysis of Gezende Dam

The dynamic characteristics of Gezende Dam were examined using modal analysis. Modal analysis was performed by utilizing the Eigenvector method. Fig. 4 shows the first four modes of the dam structure.

The first four period values observed in the system were determined as 0.09 sec, 0.05 sec, 0.03 sec, and 0.03 sec, respectively. The first four frequency values were obtained as 11.739 Hz, 20.520 Hz, 32.846 Hz, and 38.534 Hz. The participating mass ratio for mode 1 was determined as % 68.

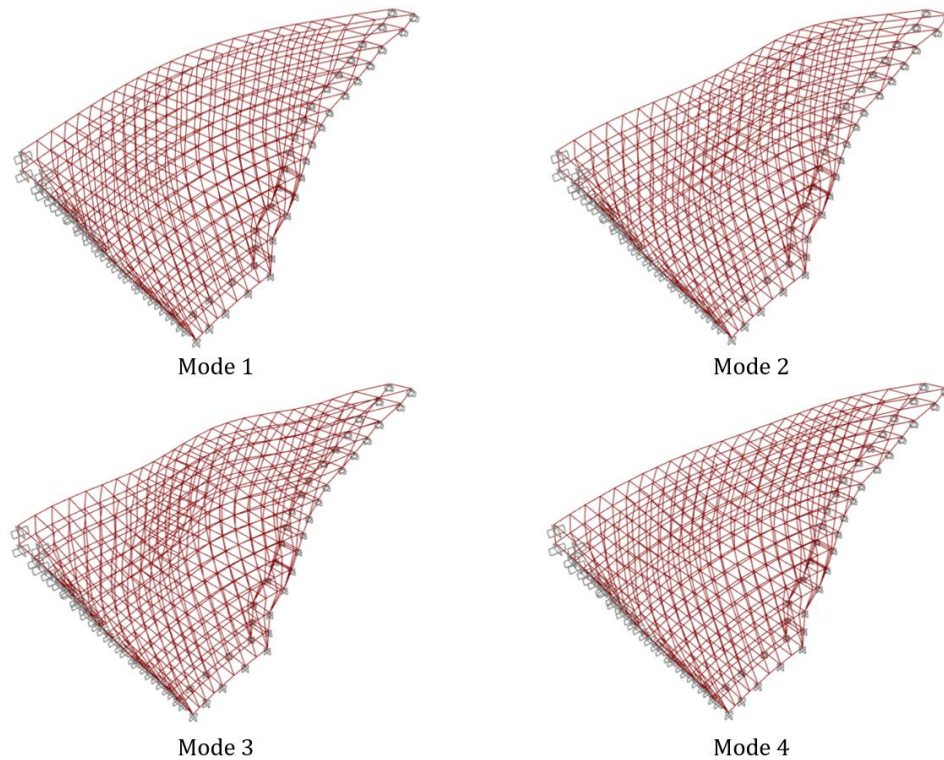


Fig. 4. The first four mode shapes of the Gezende Dam.

4. The Frequency and Spectral Content of Seismic Motions

4.1. The evaluation of the frequency domain analysis

Common methods that are used to determine frequency content include FFT, STFT, wavelet analysis and PSD analysis. FFT analysis (Cohen 1995; Mallat 1999) is carried out using signal records. FFT analysis is an effective method used for estimating dominant frequency and frequency content. While performing these analyses, seismic acceleration records are used to determine the frequency content of the earthquake. Determining frequency content plays an important role in arch dam safety. In order to evaluate the resonance potential, it is of great importance to determine the frequency of the system and the dominant frequency of the signal. Modal analysis is used to determine the frequency values of the system. It is essential to highlight that the identification of frequency content for all ground motions is carried out based on the time series of seismic motions.

In this study, Fast Fourier transform (FFT) analyses were performed using MATLAB software, and the sam-

pling interval (Δt) of the earthquake records was determined using the difference between two consecutive time values. The sampling frequency, f_s , was obtained using the relationship $1/\Delta t$. All five ground-motion records were used in the analyses. The FFT length was taken to be equal to the total number of data points (N) in the earthquake records. The frequency resolution was determined using the expression $\Delta f = f_s/N$. The positive frequency range was considered to be $0 - f_s/2$.

A Fast Fourier Transform (FFT) was performed to analyze the frequency domain characteristics of the time dependent seismic signals. The dominant frequency values were derived from the Fourier spectrum obtained. Frequency spectra of earthquakes are presented in Fig. 5. The frequency components of each ground motion were determined. Table 2 shows the natural frequency of the dam and the first dominant frequency values obtained from the FFT analysis of the ground motions. The ratio of these two frequencies is less than 1, indicating that the dominant frequency of the earthquake records does not match the natural frequency of the dam. The relationship between the dominant frequency and the natural frequency of system is highly influential in determining the resonance potential.

Table 2. Comparison of the dam's first natural frequency with the first dominant frequency of earthquakes.

Earthquake No	Earthquake Name	Record Name	The first dominant frequency of dam (Hz)	Dominant frequency of the ground-motion record (Hz)	$f_{\text{Earthquake}}/f_{\text{dam}}$
1	Coyote Lake	G01320	11.1	4.994	0.44
2	Landers	GRN180	11.1	0.543	0.05
3	Coyote Lake	G06230	11.1	0.960	0.09
4	Livermore	LM0355	11.1	5.542	0.49
5	Loma Prieta	HCH090	11.1	1.100	0.09

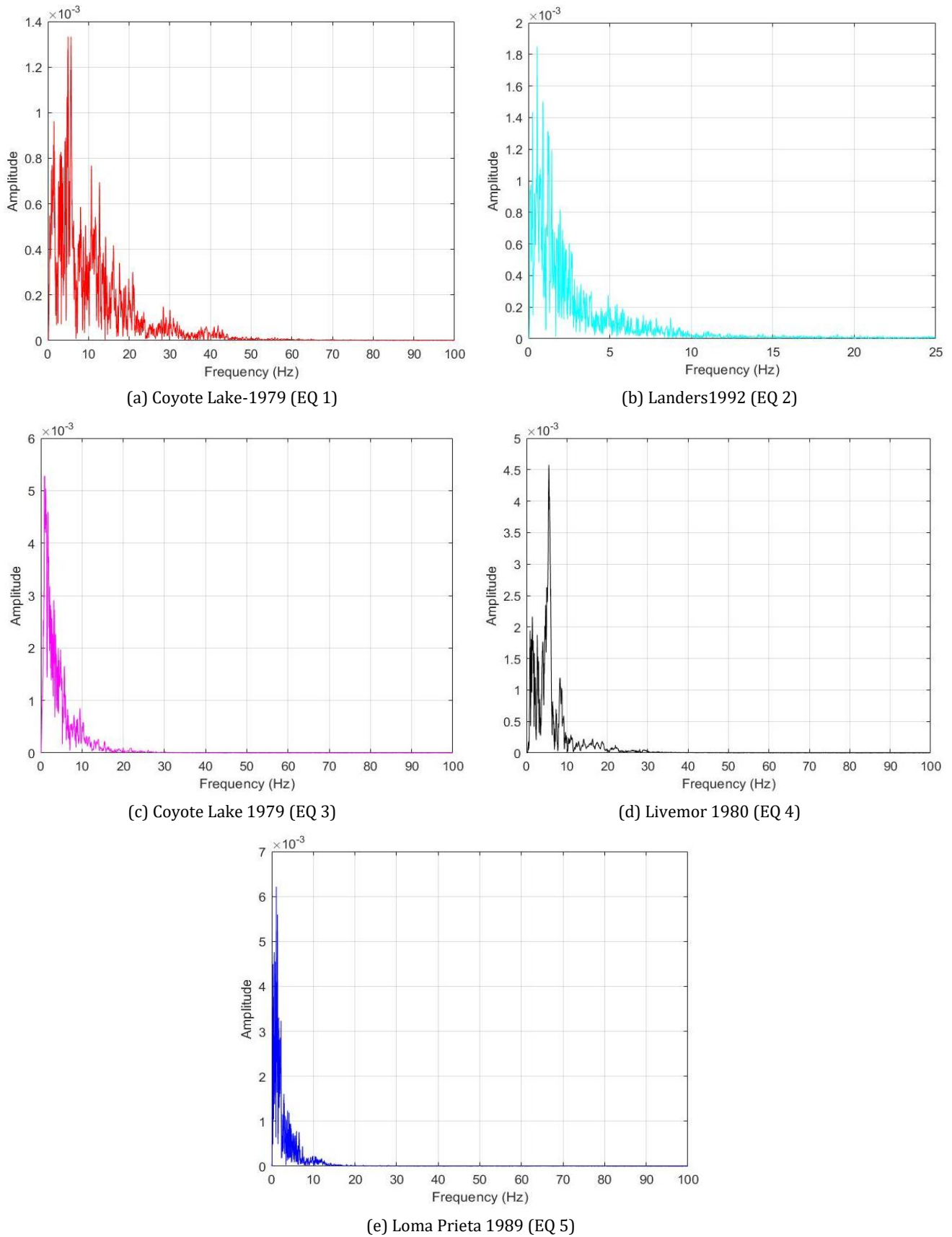


Fig. 5. Fast Fourier transform spectrum of ground motion.

Short-Time Fourier Transform analysis shows the change of frequency content depending on time. Spectrograms of earthquakes are shown in Fig. 6. While FFT indicates frequency content, spectrogram shows energy

concentrations at specific time intervals. The Δt value of the earthquake was used as the STFT sampling interval. The sampling frequency was determined using the relationship $f_s = 1/\Delta t$. For the suitability of time and fre-

quency resolution, a window of length 256 was used in STFT analyses. The number of FFT points was chosen as 512, consistent with the window length, and this value was used to provide a more detailed view of the distribution in the spectrogram. The analyses used a % 78 overlap between windows, a measure that is used to en-

sure an appropriate spectrogram. The spectrograms show that the energy content of the earthquake records varies depending on both time and frequency, with no single continuous frequency band remaining dominant throughout the entire duration. Spectrograms were obtained using MATLAB (MathWorks 2024).

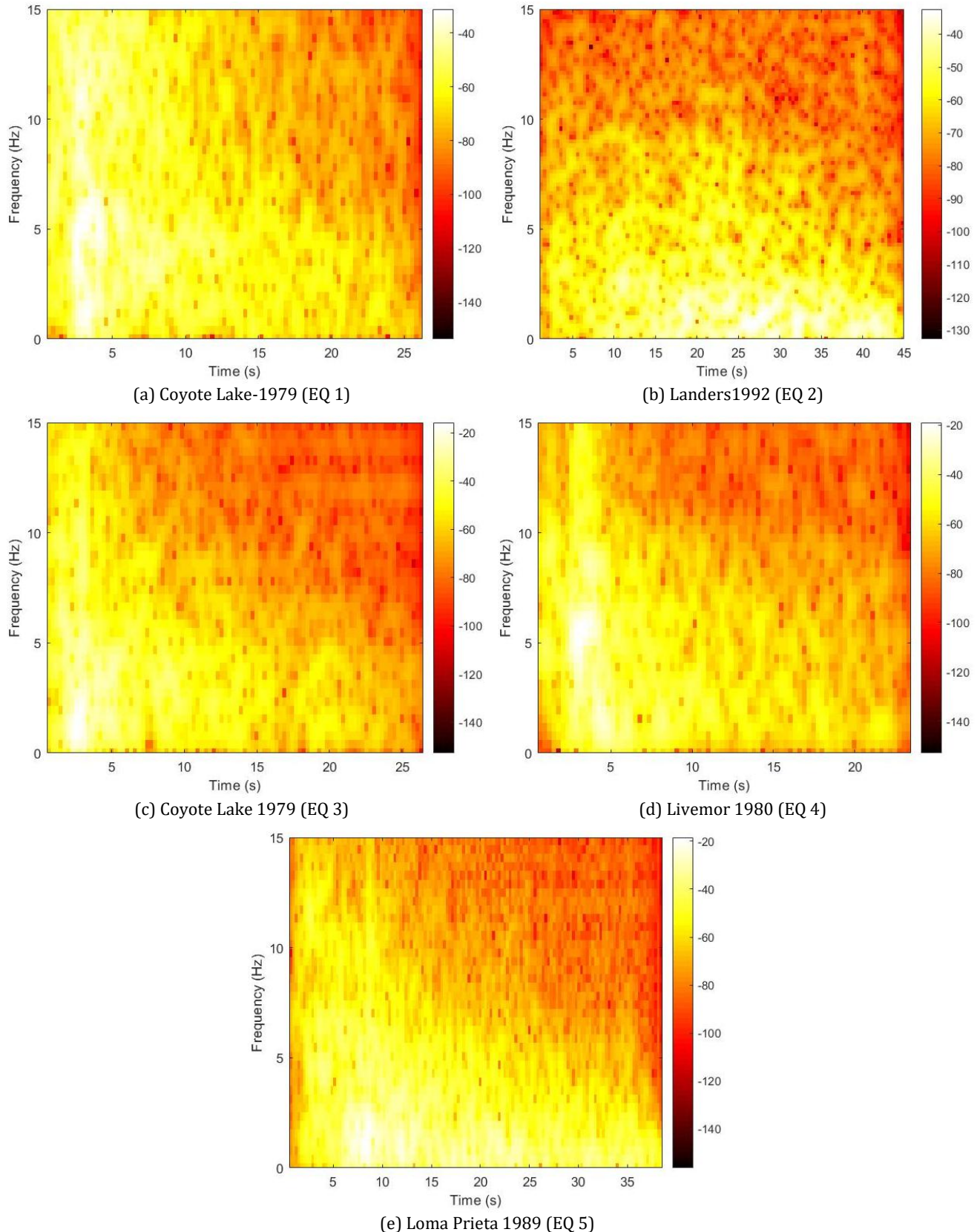


Fig. 6. Spectrograms of earthquakes.

4.2. Spectral analysis assessment

During the seismic analysis of Gezende Dam, the spectral acceleration values associated with the applied ground motion records were obtained using Seismosignal program to evaluate the spectral characteristics of the ground motion records (Seismosoft 2025). The damping ratio used when obtaining the elastic response spectra is 5%. Response spectra were obtained using a period range of 0 to 4 seconds and a period increment of 0.05 seconds.

As illustrated in Fig. 7, these response spectra were used to evaluate the variation of spectral acceleration

with period. For each earthquake record, the dominant period value corresponding to maximum spectral acceleration was determined. The spectrum curves obtained for each earthquake display differences from each other. This variation differs depending on the frequency content and the features of the earthquakes, which significantly affect the dynamic behavior of the system. The first four period values of Gezende Dam are, 0.09 sec, 0.05 sec, 0.03 sec, 0.03 sec, respectively. No correspondence is observed between these values and the period values corresponding to the maximum spectral acceleration.

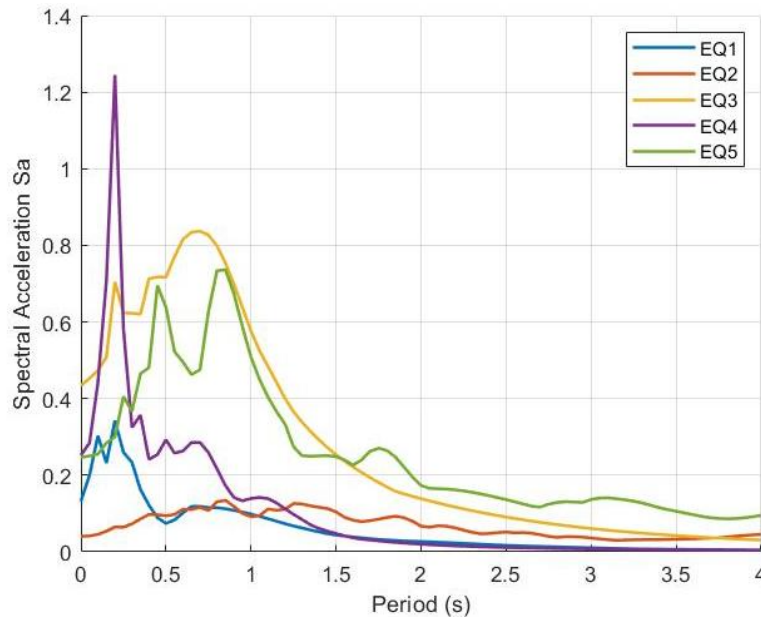


Fig. 7. The comparison of spectral acceleration of ground motions.

Response spectra of the earthquakes used in the analysis were obtained, and for each earthquake, the period values corresponding to the largest spectral acceleration were obtained. Table 3 shows a comparison of the largest period values corresponding to the spectral

acceleration with the first natural period of the structure for each earthquake. In the comparison performed, it was determined that the dominant spectral period values did not match the first natural period value of the structure.

Table 3. Comparison of the dam's first natural period value with the peak spectral acceleration period values of seismic loads.

Earthquake No	Earthquake Name	Record Name	T ₁ value of Gezende Dam (sec)	The period value of peak Sa (sec)
1	Coyote Lake	G01320	0.09	0.20
2	Landers	GRN180	0.09	0.85
3	Coyote Lake	G06230	0.09	0.84
4	Livermore	LM0355	0.09	1.25
5	Loma Prieta	HCH090	0.09	0.74

5. Identifying Structural Responses

The structural responses that resulted from applying seismic loads to the dam structure were compared. The displacement and stress values obtained for the empty and full condition of the dam are shown in Fig. 8(a-b).

The largest displacement values were obtained with values of 35.356 mm and 55.856 mm for the empty and full states of the dam in Coyote Lake (G06230) earthquake respectively. The largest stress values were obtained as 8.7666 MPa and 16.40496 MPa.

A normalization process was performed to facilitate comparison of the displacement and stress values obtained from analyses under seismic loads, considering both empty and full reservoir conditions. This process was carried out by dividing the displacement and stress values by their respective maximum values ($U_{\text{norm}}=U/U_{\text{max}}$, $S_{\text{norm}}=S/S_{\text{max}}$).

Fig. 9(a-b) illustrates the displacement and stress values obtained from the application of earthquakes with different characteristics to Gezende Dam. The strong ground motions induce amplified structural responses, such as increased stress and displacement. It was observed that the values obtained when the dam was full were greater than those obtained when it was empty; in other words, the dam's fill rate significantly affected the system's behaviour.

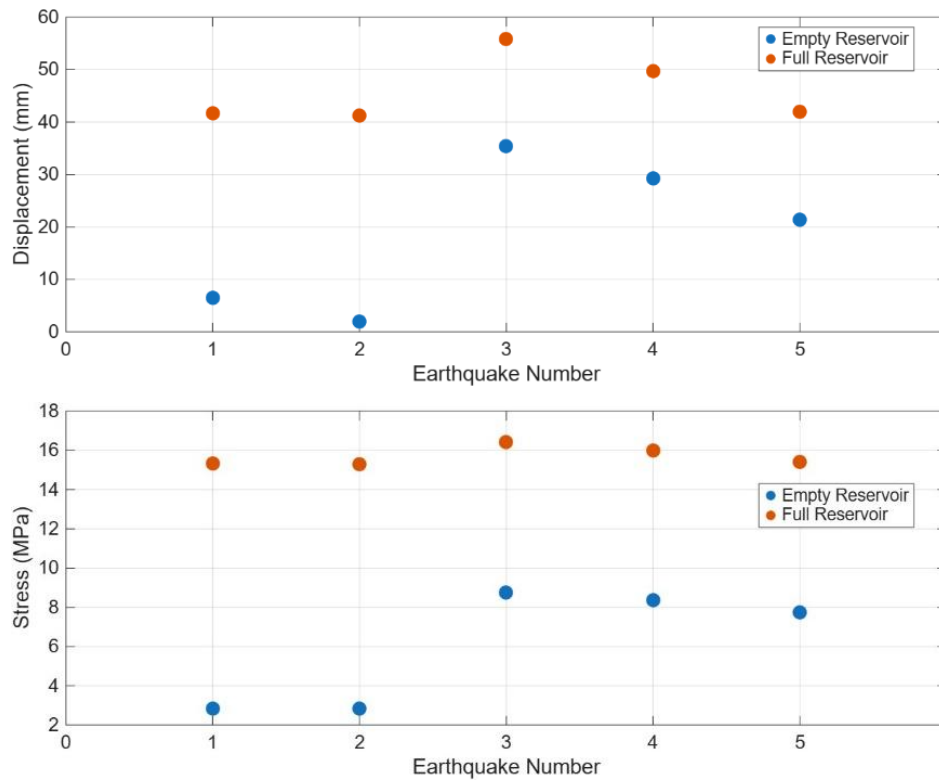


Fig. 8. Displacement and stress values.

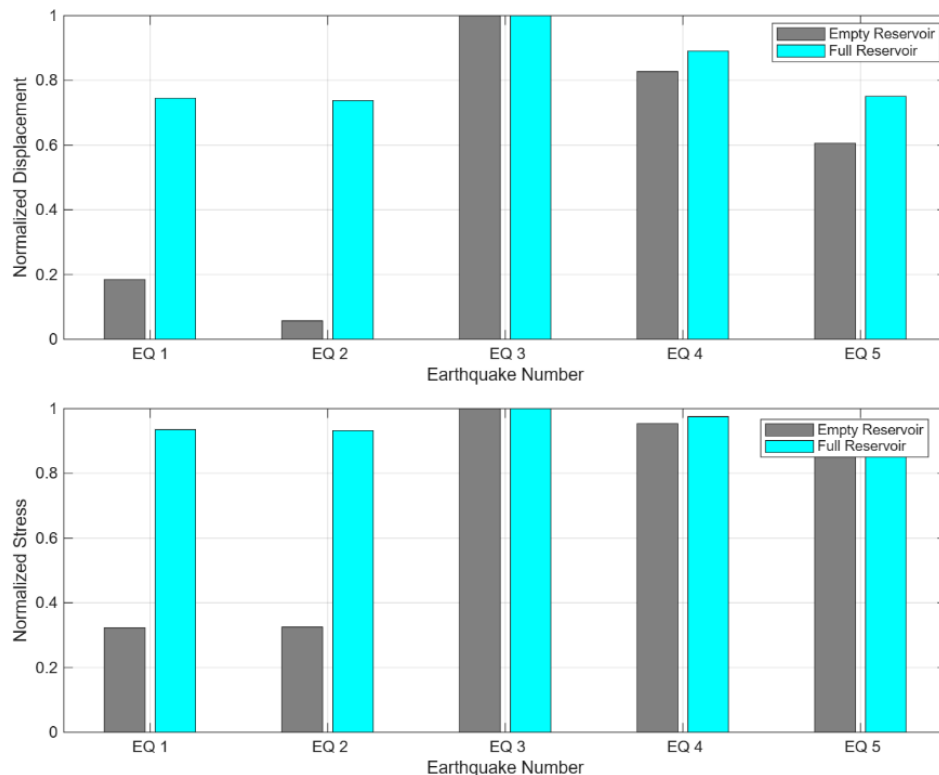


Fig. 9. Normalized displacement normalized stress values.

According to the results obtained; for all the earthquakes, the displacement values reach their maximum level at the top of the dam, while the stress values exhibit the highest values in areas close to the base. Under Coyote Lake (EQ 1), Landers (EQ 2), Coyote Lake (EQ 3), Livermore (EQ 4), Loma Prieta (EQ 5), the normalized displacement and stress values determined for the empty condition were 0.18, 0.05, 1, 0.82, 0.60 and 0.32, 0.32, 1, 0.95, 0.88 respectively. Under the full condition, these values were 0.74, 0.73, 1, 0.89, 0.75 and 0.93, 0.93, 1, 0.97, 0.93 respectively. As seen, the highest structural re-

sponses were observed during Coyote Lake ground motion. Depending on the increase of earthquake effect, inertia forces also increased, which led to the increase of inner forces.

5.1. Model validation

To evaluate the reliability of the numerical model, the results obtained were validated by comparing them with studies in the literature. Table 4 compares the stress values obtained in this study with those in the literature.

Table 4. Comparison of the present study with literature.

	This study	Fan (2015)	Zeinizadeh (2018)	Wang (2018)
Maximum Stress (MPa)	16.40	16.3	15.4	16.59
Deviation	–	% 0.61	% 6.49	% 1.15

Fan (2015) found the maximum compressive stress value at the downstream face of an arch dam as 16.3 MPa in a feasibility study. This value is quite close to the one in the current study. Zeinizadeh (2018) obtained a principal stress value of 15.4 for S1 when the load step was 150. Wang (2018), according to the trial load method, determined the compressive strength values for concrete zones A (C₁₈₀40), B (C₁₈₀35) and C (C₁₈₀30) as 18.96 MPa, 16.59 MPa and 14.22 MPa, respectively. Gezende Dam body has a concrete class of 30 MPa, and the stress value obtained from the analyses is close to 16.59 MPa. The numerical results obtained in this study were compared with values reported in the literature to assess their consistency.

6. Conclusions

In this study, the behaviour of Gezende Dam exposed to various ground motions with differing frequency content was examined.

- Different ground motion records led to the development of different structural responses in the dam. The maximum displacement and stress values were obtained during Coyote Lake earthquake. For empty and full reservoirs, the maximum displacement values were determined to be 35.356 mm and 55.856 mm, and the stress values were 8.7666 MPa and 16.40496 MPa.
- It was observed that the normalized displacement and stress values derived from seismic analyses exhibited an increase in some earthquake conditions, whereas a decline was identified in others. The internal forces demonstrate variability depending on the ground motion amplitude.
- Response spectra for the earthquakes considered were generated, and the periods corresponding to the highest spectral acceleration were determined. The values of spectral acceleration are 0.34264 g, 0.13414 g, 0.83721 g, 1.24503 g, and 0.73637 g, respectively. The peak period values were compared with the dam's first natural period, and it was determined that

the periods did not coincide. Applying the earthquake records to the system showed that no resonance potential was generated in the structure.

- To evaluate the frequency content of the earthquake data, FFT (Fast Fourier Transform) and Short Time Fourier Transform (STFT) analysis were performed. The earthquakes considered in this study were Coyote Lake (G01320), Landers (GRN180), Coyote Lake (G06230), Livermore (LMO355), and Loma Prieta (HCH090). The dominant frequency values obtained from the FFT signal analysis are 4.994, 0.543, 0.960, 5.542, and 1.100 Hz, respectively. The dominant frequency value of the Gezende Dam is 11.1 Hz. The ground motions exhibit variations in terms of their frequency content. The natural frequency value of Gezende Dam and the dominant frequencies of the ground motions were determined to be unmatched.

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Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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