ASSESSMENT OF VIBRATION CHARACTERISTICS OF BRIONES AND TERMINUS DAMS USING EARTHQUAKE RECORDINGS

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Abstract

The potential dam failure modes related to earthquakes are often the driving design criteria for new dams and the primary concern when evaluating the safety of existing dams. Ground motion recordings on dam sites at different locations were studied to estimate dams' fundamental and second mode vibration. Earthquake-based horizontal to vertical ratio (HVSR) are evaluated. Fourier amplification ratios using crest records over the abutment or downstream records are also assessed. The vibration characteristics are evaluated based on different methods and the resulting estimate of the fundamental frequency and second mode of vibration for Briones and Terminus dams are presented.

Introduction

The seismic response of earth dams is admittedly rather complicated and therefore advanced methods of dynamic analysis need to be employed to capture the actual behaviour of dams under seismic conditions. Such methods and associated advanced constitutive models do exist nowadays, but they need to be further developed and validated against known case studies, so that reliable results can be obtained for further dam analysis and design. Various methods have been developed over the years and these range from the simple numerical shear beam method up to the sophisticated nonlinear coupled dynamic analysis including consideration of reservoir-dam interaction effects. However, it is important to note, that as the methods become more sophisticated and can capture more aspects of the soil response, the nonlinearity as well as the reservoir-dam interaction during shaking, the analyses become computationally intensive.

When evaluating the seismic response of earth dams, dam fundamental frequency and second mode vibration are the key parameters in the dynamic response of a dam, can be assessed using the horizontal-to-vertical spectral ratio (HVSR) and Fourier amplification ratio from crest to abutment or downstream records. The HVSR is mostly assessed by performing microtremor measurements in the field. However, when earthquake records are available, HVSR can also be calculated using the recorded earthquake motions. Additionally, cross spectra which is defined here as the Fourier amplitude spectra of the horizontal component (FASH) of the crest records over the FASH of the abutment or downstream records are also indicative of vibration characteristics of the dam. With that purpose, our vision is to use existing ground motion recordings at earth dam sites that are part of the California Strong Ground Motion Instrumentation Program (CSMIP) database to develop a simpler approach to investigate the dynamic characteristics of dam sites. Specifically, our approach aims to compute and analyze the horizontal-to-vertical spectral ratio (HVSR) and cross spectra at sensor locations positioned at dam sites using earthquake recordings and investigate the dam resonant frequencies. For that purpose, ground motion data on dam sites at different locations (i.e., right crest, left crest, etc.) are cataloged and processed. First signal-to-noise ratios (SNR) were calculated to determine the usable frequency range and assess the quality of the ground motions. The processed motions are used to study the vibration characteristics of dams.

The HVSR is the ratio between the Fourier amplitude spectra (FAS) of the horizontal and the vertical component of microtremors was first introduced by Nogoshi and Igarashi (1970 and 1971), and widely used following the study by Nakamura (1989, 1996, 2000). Several researchers studied HVSR method, either using microtremors (mHVSR) (Nagoshi and Igarashi (1971), Nakamura (1989, 2000), Yong et al. (2013)) or strong ground motion data (eHVSR) (Lermo & Chavez-Garcia (1993), Hassani et al. (2020)), as an indicator of the subsurface conditions and can be successfully applied for identifying the fundamental resonance frequency. Earthquake-based HVSRs are calculated as the Fourier amplitude spectra ratio of the horizontal to vertical components (FASH/FASV) of the ground motion records at the surface using the intense S-wave portion and using the entire motion which are two common approaches in the literature. Studying the dam vibration characteristics, Fourier amplitude ratio can be calculated as the ratio of FFTcrest to FFTabutment or FFTdownstream records. The vibration characteristics are evaluated based on different methods and the resulting estimate of the resonance frequencies to understand the local and site-specific features for Briones and Terminus Dam sites at different locations (i.e., right crest, left crest, etc.) are presented in this study.

Description of Selected Dams

Briones Dam

Briones Dam is located in the western part of Contra Costa County within the San Francisco Bay Area (37.9135 N, 122.2092 W), and built in 1964. The dam is an earth dam and serves a primary purpose of flood control and water supply. It stands at an elevation of 189 meters, with a height of 273 feet (81.9 meters) and a crest length of 2100 feet (630 meters). In 1975, a total of nine accelerometers were installed, positioned on the center and left crests (Loc2, Loc3) as well as the left abutment (Loc1) of the dam. Figure 1 shows the plan view of the dam and the installed accelerometers (California Strong Motion Instrumentation Program, 2014). The accelerometer placed at the center crest and the one at the left crest are oriented in alignment with the dam's transverse and longitudinal directions. The sensor at the left abutment orientation was updated due to field change after 06/24/2014 from 31° and 121° to 90° and 360°. Site investigation data and cross sections of the dam could not be acquired for Briones Dam which would provide important information in understanding the dynamic behaviour of the dam. Between 1984 and 2021, Briones Dam experienced several earthquake events, and 16 of them are documented by CSMIP with recordings at the right and left crest, and the left abutment locations. These earthquakes occurred at epicentral distances ranging from 6 to 35 kilometers and have magnitudes (M_w) from 3.3 to 6.0 with peak acceleration (PGA), from 0.09 g to 0.18 g (geometric mean of the two-horizontal components). The largest PGA was recorded at the dam was during the Piedmont Area Earthquake on July 20, 2007, which had a magnitude of 4.2 and PGA of 0.18 g at the left crest of the dam. Accelerograms were bandpass filtered with at 0.30 and 40.00 Hz and instrument- and baseline-corrected by CSMIP database. Moment magnitude, epicentral ($R_{epi.}$) and hypocentral (R_h) distances and PGA at three sensor location for the 16 recorded events are provided in Table 1.

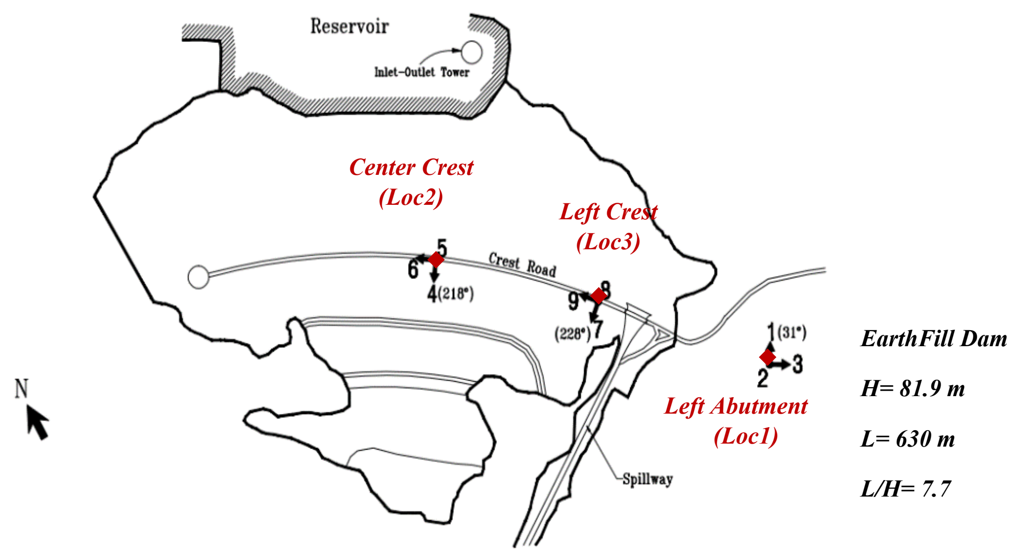


Figure 1. Plan view of Briones Dam (CGS - CSMIP Station CE 58183, diagram revised on 7/16/14, CGS: California Geological Survey)

Table 1. Information on earthquake data recorded in Briones Dam

EQ #	M_w	$R_{epi.}$ (km)	R_h (km)	Left Abutment (Loc1) PGA*	Center Crest (Loc2) PGA*	Left crest (Loc3) PGA*
2	3.6	6.5	11.1	0.03	0.02	0.03
3	4.2	12	13.3	0.09	0.13	0.18
4	6.0	35.2	37.0	0.02	0.04	0.04
5	4.0	8.8	10.0	0.06	0.04	0.07
6	4.1	9.9	19.3	0.04	0.07	0.08
7	3.5	19.6	21.2	0.01	0.01	0.01
8	4.0	7.5	11.0	0.05	0.03	0.03
9	3.8	6.3	11.5	0.06	0.03	0.03
10	3.5	6.1	11.5	0.02	0.01	0.01
11	3.9	8.4	12.5	0.04	0.07	0.04
12	3.8	7.7	14.4	0.01	0.02	0.01
13	4.4	6.6	14.0	no data	0.03	0.03
14	3.5	7	11.6	0.02	0.01	0.02
15	3.3	7	11.6	0.02	0.01	0.01
16	4.5	13.5	19.5	0.04	0.12	0.11
17	3.9	24.3	26.0	0.01	0.01	0.02

* PGA units are in g and the values presented as the geometric mean of the two horizontal component

Terminus Main and Auxiliary Dams

Terminus main and auxiliary dams are located on Kaweah River in Tulera County, California (36.4102 N, 119.0050W), and built in 1962. The dam is an earth dam and serves a primary purpose of flood control and irrigation water supply. It stands at an elevation of 297 meters. The main dam has a height of 255 feet (78 meters) and a crest length of 2375 feet (724 meters) (data taken from http://cdec.water.ca.gov/) and the auxiliary dam has a height of 144 feet (44 meters) and a crest length of 876 feet (267 meters) approximately measured from the Google Earth. A total of five accelerometers were installed, positioned on the right crest (Loc5), mid-slope (Loc6), right abutment (Loc4), downstream (Loc3) and upper tower (Loc7) of the main dam. Two accelerometers were installed on auxiliary dam, positioned on the center crest (Loc2) and right abutment (Loc1) of the dam. Figure 2 shows the plan view of the dams and the installed accelerometers by California Strong Motion Instrumentation Program along with simplified plan view sketches prepared for both dams. The accelerometers placed at the center crest and abutments are oriented in alignment with the dams' transverse and longitudinal directions for both structures. Site investigation data and cross sections of the dams could not be acquired for Terminus Dams which would provide important information in understanding the dynamic behaviour of the dam.

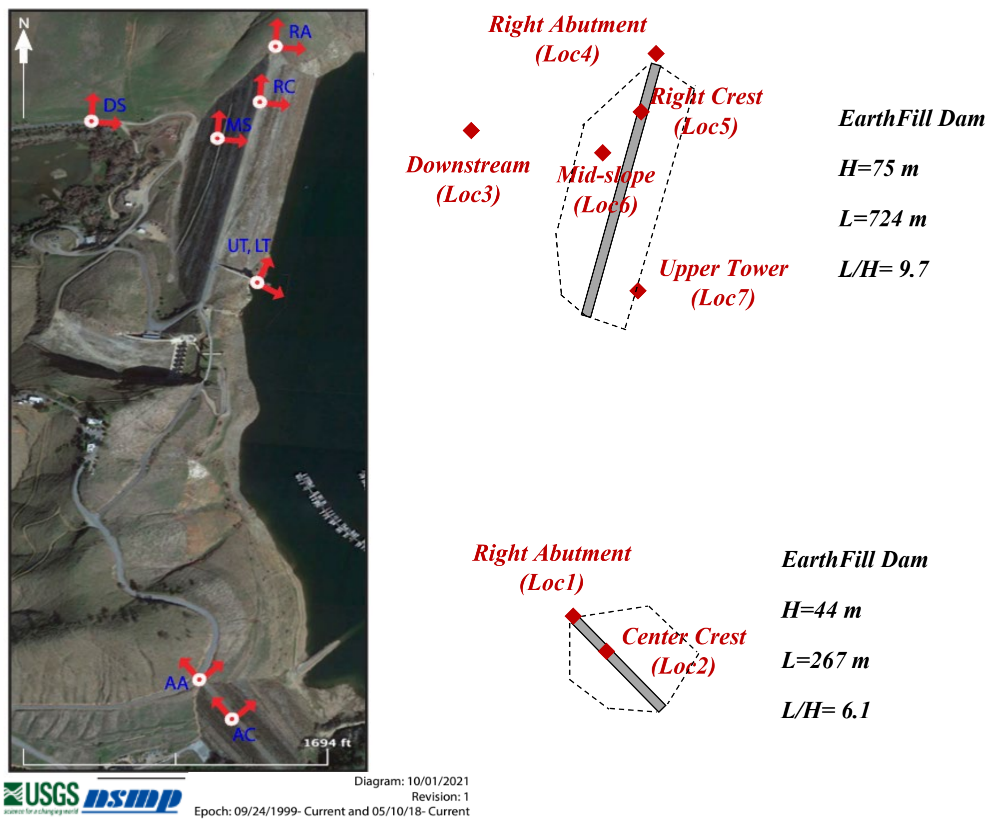


Figure 2. Plan view of Terminus main and auxiliary dams (Terminus Dam NSMP Station 1098, diagram revised on 10/01/21, NSMP: National Strong Motion Project)

CMSIP database provides two earthquake recordings for Terminus Dams. 4th of July 2019 and 5th of July 2019 Ridgecrest Earthquakes occurred at epicentral distances of 156 and 145 km kilometers and have magnitudes (M_w) of 6.4 and 7.1. The peak acceleration (PGA) at the main dam right crest was recorded as 0.03 g and 0.05 g (geometric mean of the two-horizontal components) for 6.4 and 7.1 magnitude events respectively. Similarly, the peak acceleration (PGA) at the auxiliary dam crest was recorded as 0.05 g and 0.08 g for 6.4 and 7.1 magnitude events. Accelerograms were bandpass filtered at 0.10 and 40.00 Hz and instrument- and baseline-corrected by the CSMIP database. Moment magnitude, epicentral ($R_{epi.}$) and hypocentral (R_h) distances, and PGA at 5 sensor locations for the two recorded events are provided in Table 2.

Table 2. Information on earthquake data recorded in Terminus Dam

EQ #	**1**	**2**
M_w	6.4	7.1
$R_{epi.}$ (km)	156.1	145.2
R_h (km)	156.5	145.4
Location	**PGA (g)**	
Loc 1-Aux Dam Right Abutment	0.01	0.02
Loc 2-Aux Dam Crest	0.05	0.08
Loc 3-Main Dam Downstream	0.01	0.02
Loc 4-Main Dam Right Abutment	0.01	na
Loc 5-Main Dam Right Crest	0.03	0.05

* PGA units are in g and the values are presented as the geometric mean of the two-horizontal component

Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio can be defined as the ratio of the Fourier amplitude spectrum of the signal (S-wave) time window by the spectrum of the pre-event noise. SNR provides information on the quality of the ground motions if the amplitude of the signal is strong enough (e.g., SNR>2-10) at a given frequency to be used in various applications (e.g., HVSR analysis). Hence, SNR calculation provides a usable frequency range and allows us to detect high-quality data.

For the ground motion dataset of Briones and Terminus Dam, SNRs are calculated for 55 earthquake recordings. For this study we followed the procedure describe in Kishida et al. (2016) which provides a semi-automated procedure for windowing time series and computing Fourier amplitude spectra to extract various waves. Different window series (pre-event noise, P-wave and S-wave and coda wave) were extracted, and visual examination of the recording was performed to attain a better-quality dataset. Fourier amplitude spectra of different windows were calculated and smoothed with Konno and Ohmachi (1988) (b=20) functions. SNR cutoff value of 3 (e.g., Field and Jacob, 1995) is used to determine the usable frequency range. We have also chosen to carefully assess the vertical components data quality which most of the time has higher noise than horizontal components, as the one of the purposes of the SNR calculation is to compute HVSR in this study.

An illustrative example is shown to present the extraction of time windows and calculation of SNR following the procedure by Kishida et al (2016). Figure 3a shows the vertical direction of the acceleration time history of El Cerrito Earthquake of 5th of March 2012 (EQ11) recorded at the left crest (Loc3) of Briones Dam. M_w is 3.93 and hypocentral distance is 12.46 km for this event. Figure 3b shows the different window series (pre-event noise, P-wave and S-wave and coda wave) and Figure 4c presents the FAS of the signal and noise window series. SNR with cutoff limits of 3-5-10 is plotted on Figure 3d along with the usable frequency range of 0.1 to 8 Hz which is determined with an SNR cutoff value of 3. The same examination was performed for the transverse and longitudinal components as well. The resulting usable frequency range is determined by comparing the results of three component data as 0.1-8 Hz. 45 recording 3 component data, in total 135 acceleration time history are examined for Briones Dam. The lowest usable frequency range varies between 0.1-1.1 Hz and the highest usable frequency ranges between 7.9-50 Hz.

A similar exercise is performed for 10 recording 3 component data, in total 30 acceleration time history for Terminus Dams. When the event noise window is not adequate (shorter than 10 sec), coda waves are used to evaluate the quality of data. 4th of July 2019 and 5th of July 2019 Ridgecrest Earthquakes recorded at Terminus Dam had short noise durations hence signal to coda ratio was assessed with a cutoff value of 2 to determine the usable frequency range. The lowest usable frequency range varies between 0.3-0.5 Hz and the highest usable frequency of 40 Hz for the records at Terminus Dams.

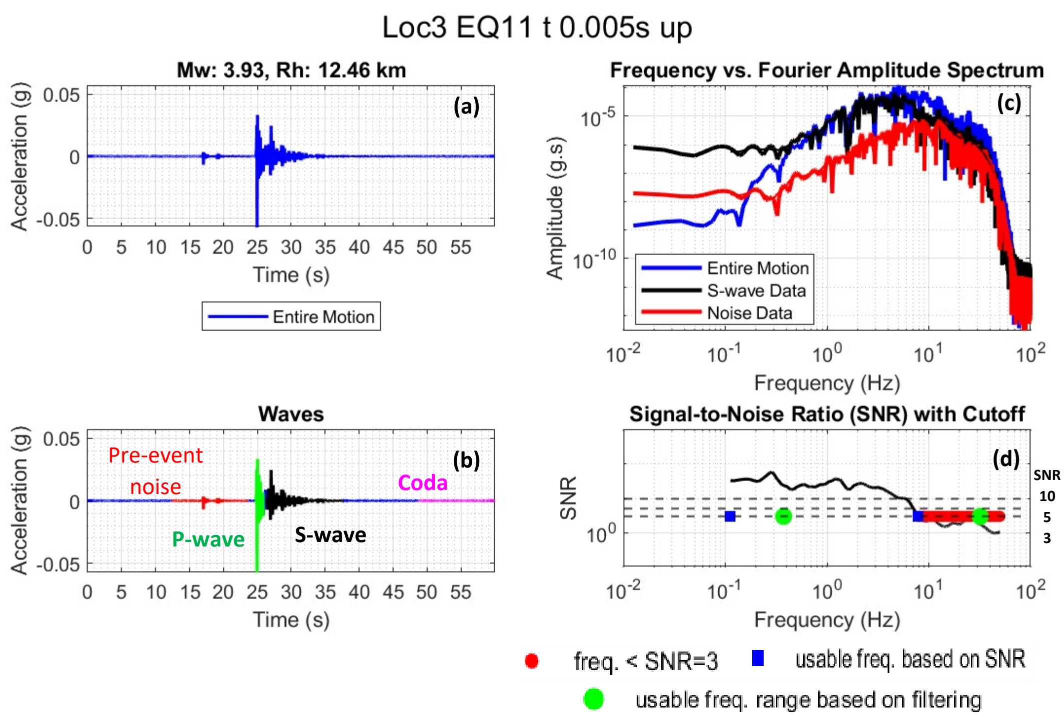


Figure 3. (a) Acceleration time history of El Cerrito Earthquake of 5th of March 2012 (EQ11) recording at left crest (Loc3) of Briones Dam in vertical direction, (b) different window series (pre-event noise, P-wave and S-wave and coda wave), (c) FAS of the Signal and Noise window series, (d) SNR with cutoff limits of 3-5-10.

Horizontal-to-Vertical Spectral Ratio

There exist several different approaches to assess HVSR based on ground motion data. One of the most common approaches is using the intense S-wave part of the records with a SNR above a certain cutoff. In this approach Fourier amplitude spectra ratio of the horizontal to vertical components (FAS_H/FAS_V) of the ground motion records using the intense S-wave portion is calculated (e.g., Kawasee et al 2011, Ktenidou et al 2015). Another alternative is using the complete waveforms (typically P_{wave} arrival to end of S_{coda}). (e.g., Zhu et al 2020). After calculating HVSR for each event, the logarithmic mean and standard deviation of the HVSR curve at each dam sensor location are calculated as given in Equation 1 and 2. The resonant frequencies of dam are defined as the peak frequencies of the average HVSR curve. Note that 'n' is the number of recordings at dam in Equations 1 and 2.

$$\ln\left(\overline{HVSR}(f)\right) = \frac{\left(\sum_{j=1}^{n} \ln\left(HVSR_j(f)\right)\right)}{n} \qquad \text{Eq. 1}$$

$$stdev(f) = \sqrt{\frac{\sum_{j=1}^{n}\left(\ln\left(HVSR_j(f)\right) - \ln\left(\overline{HVSR_j}(f)\right)\right)^2}{n-1}} \qquad \text{Eq. 2}$$

In this study, we calculated HVSR by using entire and S-wave portion approaches and compared the resultant vibration characteristics with Fourier amplification ratios at dam sites. The result of the HVSR analysis for the Briones and Terminus dams will be discussed in detail next.

Briones Dam

We have attempted to calculate HVSR in the longitudinal and transverse (upstream-downstream) direction of the dam to determine the vibration characteristics (first (fundamental) and second mode) of Briones Dam at Center Crest (Loc2) and Left Crest (Loc3) separately.

Figure 4a and b and Figure 5a and b present the HVSR results of 16 earthquake data (gray line) along with the logarithmic mean (solid line) and standard deviation (dashed line) of HVSR curves at the center crest (Loc2) and left crest (Loc3) in transverse and longitudinal directions using the intense part of the motions (S-wave). Two vertical dashed lines HVSR=0.5 and 2 are also plotted to investigate the amplifications which are greater than ~2. The first mode (fundamental) frequencies of the Briones dams are determined as 1.2 and 1.0 Hz at center crest (Loc2) in longitudinal and transverse directions respectively and 0.9 Hz at left crest (Loc3) in both directions. The second mode of vibration was observed at 6.1 Hz and 4.7 Hz at center crest (Loc 2) in longitudinal and transverse directions respectively. Whereas second mode peaks were observed at 3.6 Hz and 3.7 Hz at left crest (Loc3) in longitudinal and transverse directions respectively.

The HVSR using the same set of earthquake motions are also calculated using the entire record. Figure 6a and b and Figure 7 ab and b present the HVSR results of 16 earthquake data (gray line) along with the logarithmic mean (solid line) and standard deviation (dashed line) of HVSR curves at the center crest (Loc2) and left crest (Loc3) in longitudinal and transverse directions. The first mode (fundamental) frequencies of the Briones dams are determined as 1.2 and 1.0 Hz at center crest (Loc2) in longitudinal and transverse directions and 0.9 Hz at left crest (Loc3) in both directions. The second mode of vibration was observed at 5.9 Hz at center crest (Loc 2) in longitudinal and no clear peak was observed in transverse directions. Whereas second mode peaks were observed at 3.6 Hz at left crest (Loc3) in longitudinal and transverse directions.

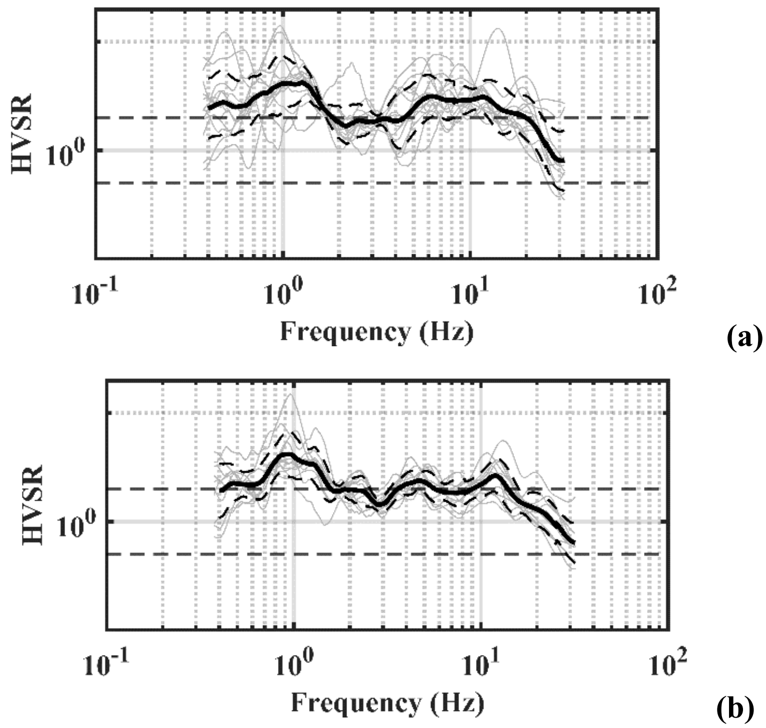


Figure 4. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using S-wave at the center crest (Loc2) in a) longitudinal and b) transverse directions.

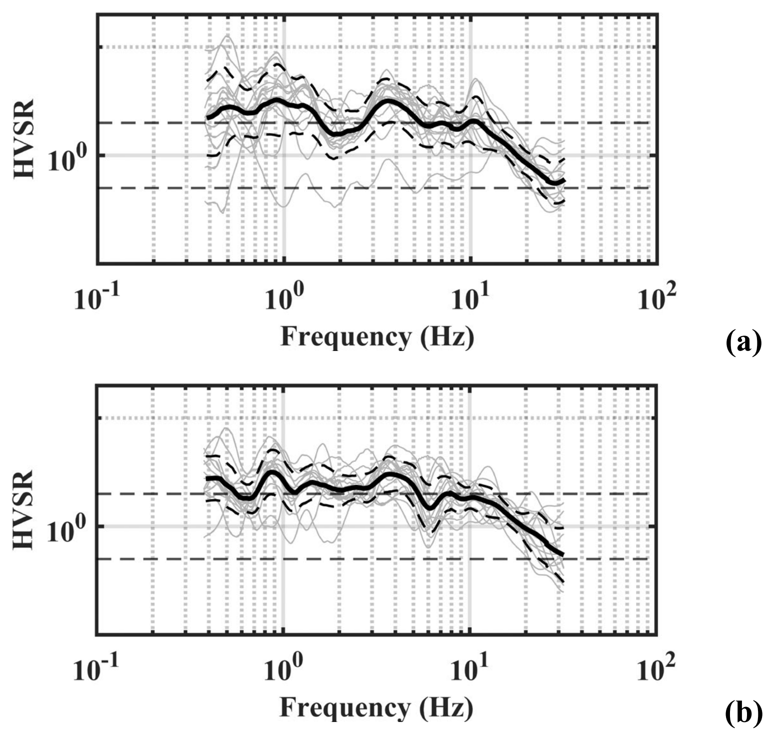


Figure 5. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using S-wave at the left crest (Loc3) in a) longitudinal and b) transverse directions.

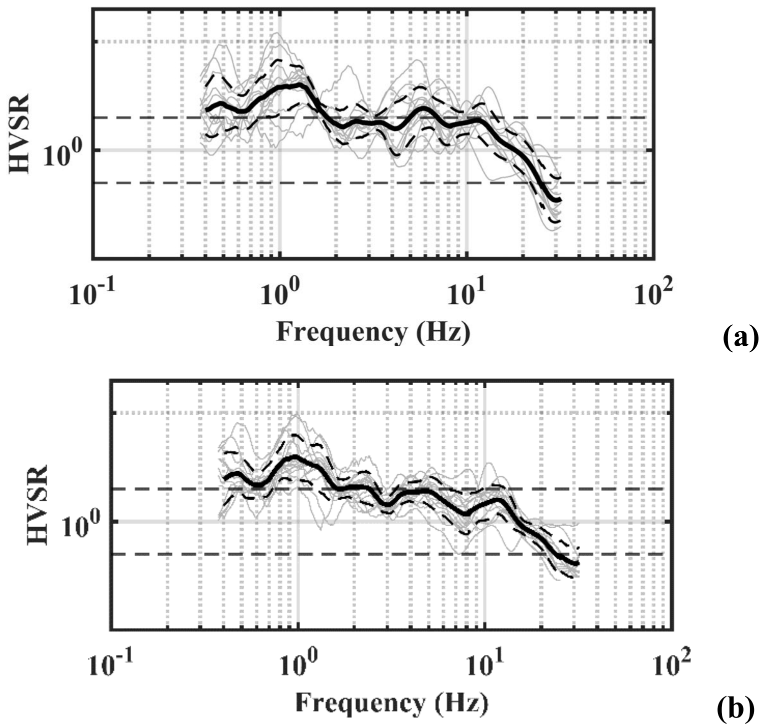


Figure 6. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using entire record at the center crest (Loc2) a) in longitudinal and b) transverse direction.

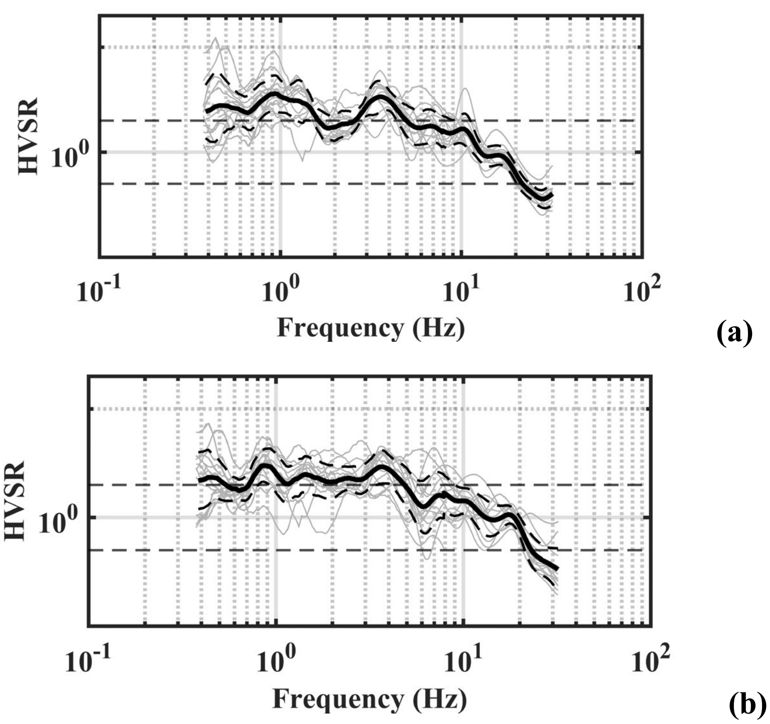


Figure 7. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using entire record at the left crest (Loc3) a) in longitudinal and b) transverse direction.

Terminus Dam

HVSR in longitudinal and transverse (upstream-downstream) direction of the Terminus main and auxiliary dams are also calculated to determine the vibration characteristics (first (fundamental) and second mode) at the main dam right crest (Loc5). Figure 8a and b presents the HVSR results of 2 earthquake data (gray line) along with the logarithmic mean (solid line) and standard deviation (dashed line) of HVSR curves at the right crest (Loc5) in transverse and longitudinal directions using the intense part of the motions (S-wave). The first mode (fundamental) frequencies of the Terminus dams are determined as 1.9 and 1.7 Hz at right crest (Loc5) in longitudinal and transverse directions respectively. The second mode of vibration was observed at 9.6 Hz and 9.8 Hz at right crest (Loc5) in longitudinal and transverse directions being less clear in longitudinal direction.

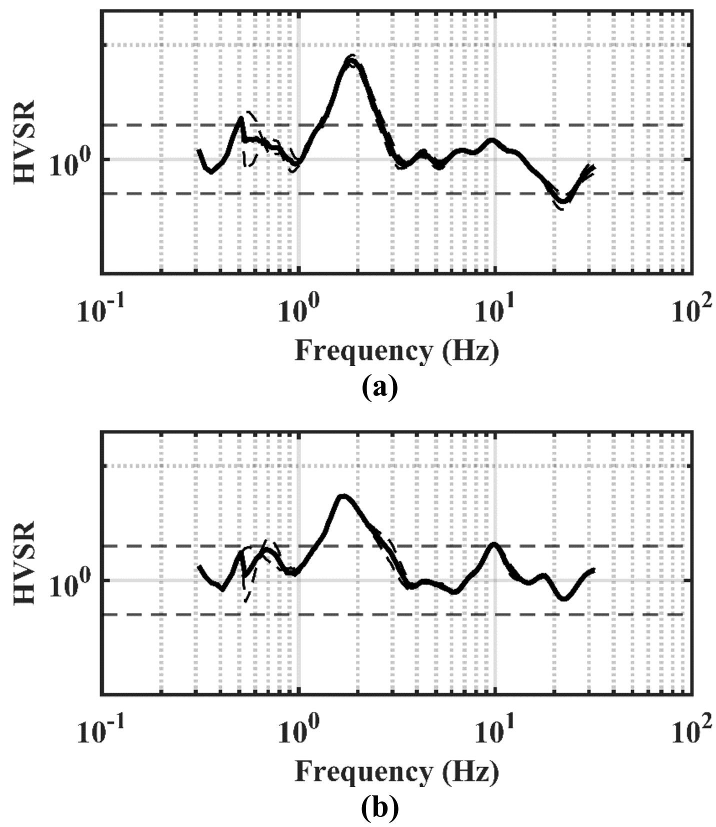
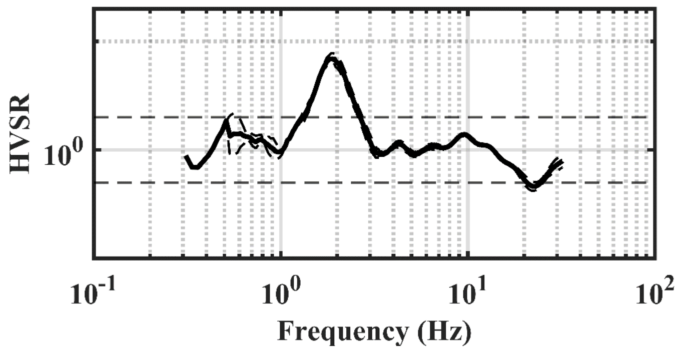
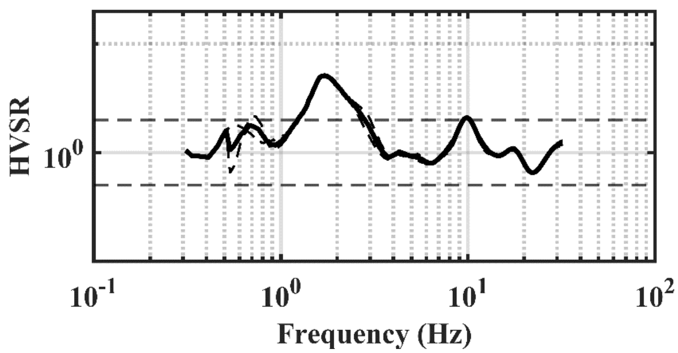


Figure 8. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using S-wave at the main dam right crest (Loc5) in a) longitudinal and b) transverse directions.

The HVSR using the same set of earthquake motions are also calculated using the entire record. Figure 9a and b present the HVSR results of 2 earthquake data (gray line) along with the logarithmic mean (solid line) and standard deviation (dashed line) of HVSR curves at the right crest (Loc5) in longitudinal and transverse directions. The first mode (fundamental) frequencies of the Terminus dams are determined as 1.9 and 1.7 Hz at right crest (Loc5) in longitudinal and transverse directions. The second mode of vibration was observed at 9.7 Hz and 10 Hz in longitudinal and transverse directions again less clear in longitudinal direction. First (fundamental) and second mode vibrations determined by HVSR using either S-wave or entire motion were around 1.8 Hz and 9.8 Hz for Terminus Dam.



(a)

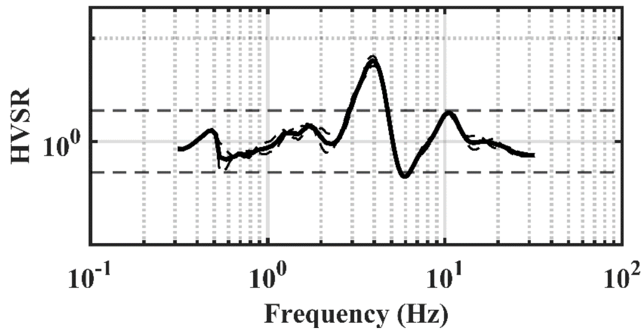


(b)

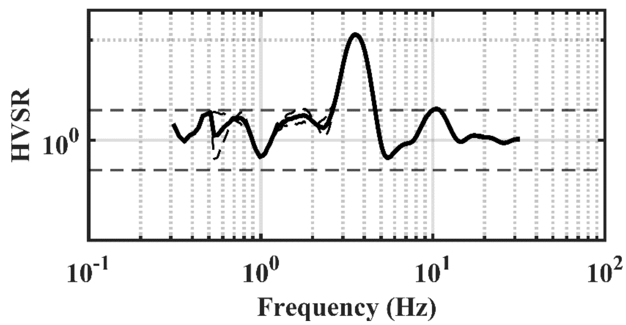
Figure 9. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using entire motion at the main dam right crest (Loc5) in a) longitudinal and b) transverse directions.

Terminus Auxiliary Dam

We have also calculated HVSR in the longitudinal and transverse (upstream-downstream) direction of the auxiliary dam to determine the vibration characteristics (first (fundamental) and second mode) at center crest (Loc2). Figure 10a and b presents the HVSR results of 2 earthquake data (gray line) along with the logarithmic mean (solid line) and standard deviation (dashed line) of HVSR curves at the center crest (Loc2) in transverse and longitudinal directions using the intense part of the motions (S-wave). The first mode (fundamental) frequencies of the Terminus auxiliary dam are determined as 4 Hz and 3.6 Hz at center crest (Loc2) in longitudinal and transverse directions. The second mode of vibration was observed at 10.4 Hz at center crest (Loc 2) in longitudinal and transverse directions. The HVSR using the same set of earthquake motions are also calculated using the entire record. Figure 11a and b present the HVSR results of two earthquake data using entire records at the center crest (Loc2) in longitudinal and transverse directions. The first mode (fundamental) frequencies of the Terminus auxiliary dam are determined as 3.9 Hz and 5.1 Hz at center crest (Loc2) in longitudinal and transverse directions. The second mode of vibration was observed at 10.6 Hz at and 10.9 Hz at the center crest (Loc 2) in longitudinal transverse directions. The first (fundamental) and second mode vibrations as determined by HVSR using either S-wave or entire motion were around 3.8 Hz and 10.5 Hz for Terminus Dam.

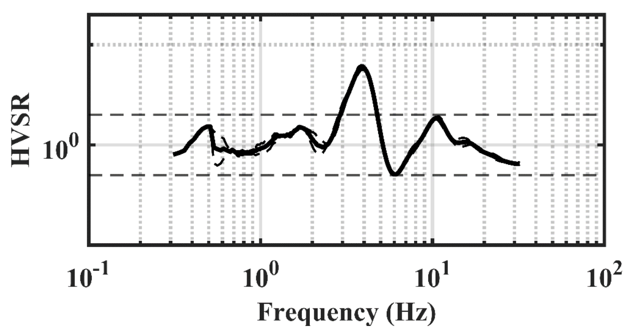


(a)

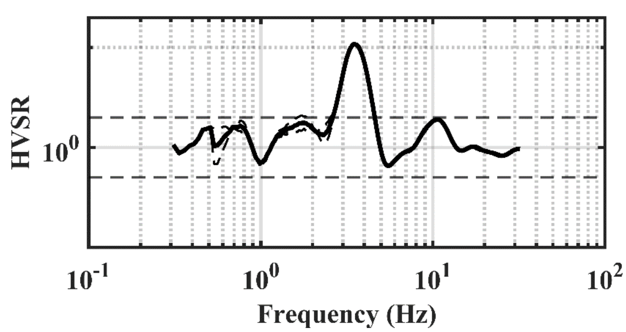


(b)

Figure 10. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using S-wave at the auxiliary dam center crest (Loc2) a) longitudinal and b) transverse directions.



(a)



(b)

Figure 11. HVSR results of earthquake data (gray line) along with the mean (solid line) and standard deviation (dashed line) of HVSR curves using entire motion at the auxiliary dam center crest (Loc2) in a) longitudinal and b) transverse directions.

Crest to Abutment or Downstream Ratio

The ratio of Fourier amplitude spectrum of the records at crest (FFT_{crest}) to abutment ($FFT_{abutment}$) or downstream ($FFT_{downstream}$) records are calculated for Briones and Terminus dams at different locations (i.e., right crest, left crest, etc.). After calculating crest to abutment ratios for each event the mean and standard deviation are calculated similarly described for HVSR in equations 1 and 2. The resonant frequencies of dam are defined as the peak frequencies of the average crest to abutment or downstream curve.

Briones Dam

The ratio of crest to abutment records are calculated for Briones Dam at each sensor location: center and left crest (Loc2 and Loc3, see Figure 1) in longitudinal and transverse directions. The site conditions at the abutment site are not known, however the HVSR results at the abutment site show no low-frequency peaks as expected for a rock site, hence they are used as a reference site. The FAS ratio of the crest records (Loc2&3) to the abutment records (Loc1) (e.g. $FAS_{H,Loc2}/FAS_{H,Loc1}$ and $FAS_{H,Loc3}/FAS_{H,Loc1}$) are calculated for 16 earthquake events recorded at Briones Dam. Figures 12a-b and c-d present crest to abutment ratio results of 16 earthquake data along with the logarithmic mean and standard deviation at center crest ($FAS_{H,Loc2}/FAS_{H,Loc1}$) and left crest ($FAS_{H,Loc3}/FAS_{H,Loc1}$) in longitudinal and transverse directions, respectively. The first peak frequencies are determined as 1.2 and 1.3 Hz at center crest (Loc2) in longitudinal and transverse directions respectively and less clear peaks at 1.2 Hz and 1.4 Hz at left crest (Loc3). The second peak was observed at 5.5 Hz and 3.0 Hz at center crest (Loc 2) in longitudinal and transverse directions whereas second mode peaks were observed at 3.0 Hz and 3.4 Hz at left crest (Loc3) in longitudinal and transverse directions respectively.

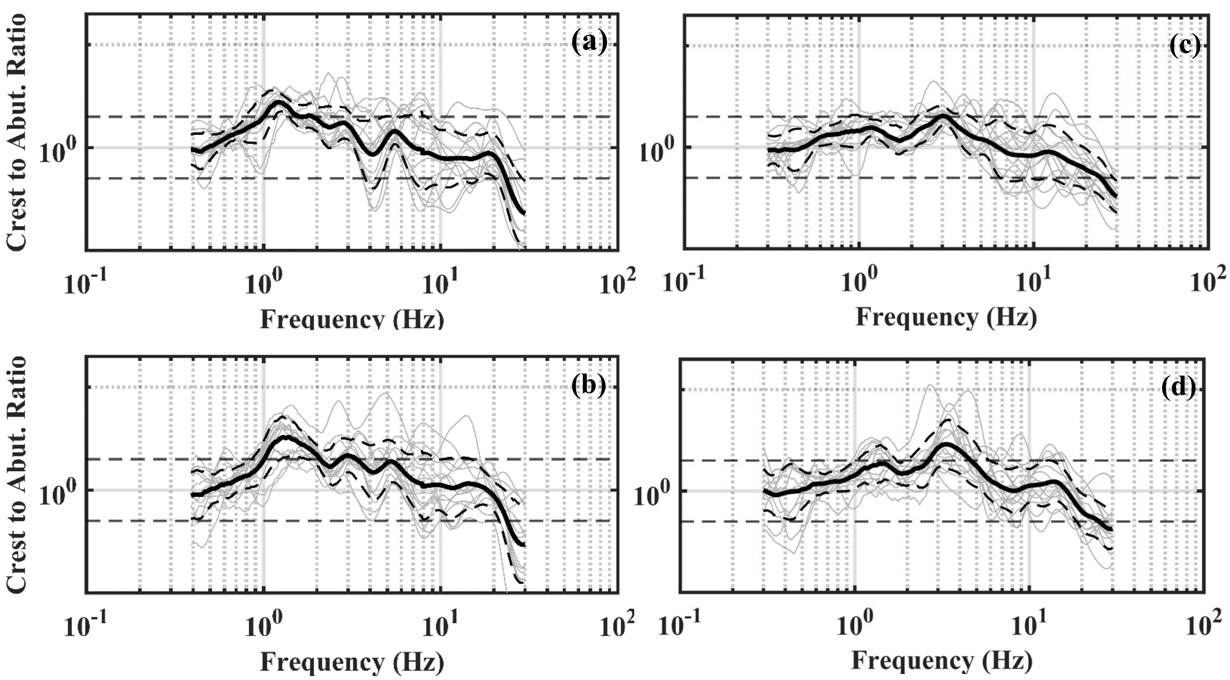


Figure 12. Crest to abutment ratio results of 16 earthquake data along with the mean and standard deviation at a) center crest (Loc2) in longitudinal and b) transverse directions, c) left crest (Loc3) in longitudinal and d) transverse directions.

Terminus Main Dam

The ratio of crest to abutment or downstream records are calculated for Terminus Dam at right crest (Loc5, see Figure 2) in longitudinal and transverse directions. The FAS ratio of the right crest records (Loc5) to the right abutment records (Loc4) (e.g. $FAS_{H,Loc5}/FAS_{H,Loc4}$) and crest to downstream ratio which is ratio of the right crest records (Loc5) to the downstream records (Loc3) (e.g. $FAS_{H,Loc5}/FAS_{H,Loc3}$) are calculated for the two recorded events. Figures 13a and b present right crest to abutment ratio results at right crest in longitudinal and transverse directions, respectively. The first peak frequencies are determined as 2 Hz at center crest (Loc5) in longitudinal and transverse directions respectively. No clear second peaks were observed when assessing crest to abutment ratios at Terminus Dam except a second peak around 10 Hz in transverse directions. Similarly crest to downstream ratios presented in Figure 13 c and d indicated first peak around 2 Hz in both directions with no clear second peak at right crest.

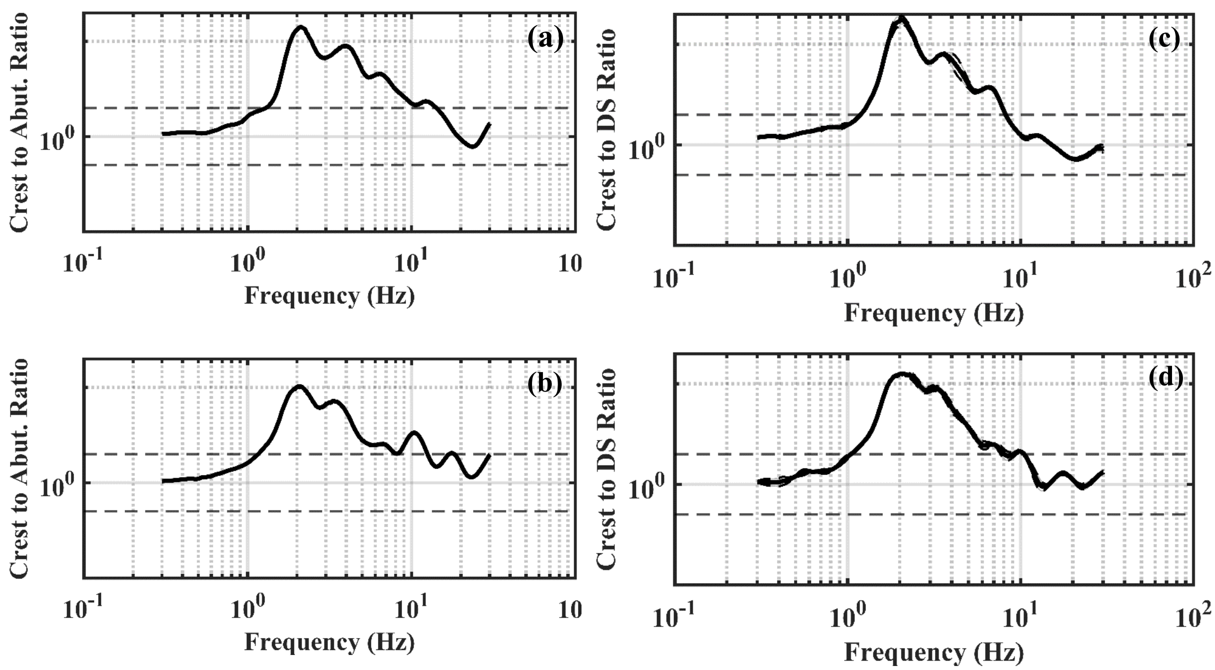
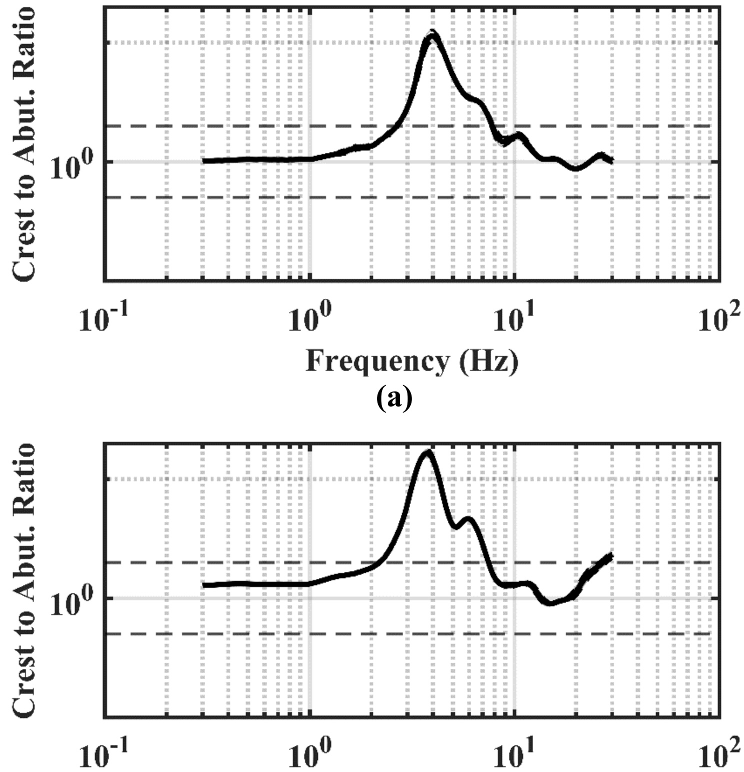


Figure 13. Crest to abutment ratio results of 2 earthquake data at a) right crest (Loc5) in longitudinal and b) transverse directions and crest to downstream ratio results of 2 earthquake data along with the mean and standard deviation at c) right crest (Loc5) in longitudinal and d) transverse directions.

Terminus Auxiliary Dam

Crest to abutment ratios are calculated as explained in the previous sections for Terminus auxiliary dam center crest (Loc2) ($FAS_{H,Loc2}/FAS_{H,Loc1}$) for 2 earthquake events as shown in Figure 14a and b. The first peak frequencies are observed around 4 Hz at center crest (Loc 2) in longitudinal and transverse directions with no secondary peaks.



(b)

Figure 14. Crest to abutment ratio results of 2 earthquake data along with the mean and standard deviation at a) center crest (Loc2) in longitudinal and b) transverse directions.

Interpretation of Results and Comparison with Available Literature

Table 3 presents the first and second mode frequency values obtained for Briones Dam's center crest and left crest locations in transverse and longitudinal direction with respect to dam body. HVSR using S_{wave} and entire records and crest to abutment ratios at center crest (Loc 2) of Briones Dam in transverse and longitudinal directions indicate similar first mode frequencies ranges 1.0-1.3 Hz. Second mode frequencies are determined as 4.7-6.1 Hz from HVSR results and 3.0-5.5 Hz from crest to abutment ratio. At left crest location (Loc3) first peak observed around 0.9-1.4 Hz for Briones Dam. Second mode frequencies are determined as 3.6-3.7 Hz from HVSR results and 3.0-3.4 Hz from crest to abutment ratio at left crest.

Table 4 presents the first and second mode frequency values obtained at main and auxiliary Terminus Dams' crest locations in transverse and longitudinal direction with respect to dam body. HVSR using S_{wave} and entire record and crest to abutment or downstream ratios at Terminus main dam right crest (Loc 5) in transverse and longitudinal directions indicate similar first mode frequencies ranges 1.7-1.9 Hz and from crest to abutment/downstream ratio as 1.9-2.2 Hz. Second mode frequencies at the same location are determined as 9.6-10 Hz from HVSR results and no second mode peaks were observed from crest to abutment ratio. HVSR using S_{wave} and entire record and crest to abutment or downstream ratios at Terminus auxiliary dam center crest (Loc2) in transverse and longitudinal directions indicate similar first mode frequencies ranges 3.5-4.0 Hz. Second mode frequencies at the same location are determined as 10.4-10.9 Hz from HVSR results and no second mode peaks were observed from crest to abutment ratio.

Table 3. Fundamental and second mode frequency values obtained by different methods in Briones Dam at center and left crest.

Method	Direction	Freq. (Hz) Center crest (Loc2)	Freq. (Hz) Left Crest (Loc3)
$HVSR_{S\text{-}wave}$	Longitudinal	1.2/6.1	0.9/3.6
	Transverse	1.0/4.7	0.9/3.7
$HVSR_{entire}$	Longitudinal	1.2/5.9	0.9/3.6
	Transverse	1.0/*	0.9/3.6
Crest/Abutment ratio	Longitudinal	1.2/5.5	1.2*/3.0
	Transverse	1.3/3.0	1.4*/3.4

Table 4. Fundamental and second mode frequency values obtained by different methods in Terminus Dams at right and center crest.

Method	Direction	Freq. (Hz) Main Dam Right Crest (Loc5)	Freq. (Hz) Aux. Dam Center Crest (Loc2)
$HVSR_{S\text{-}wave}$	Longitudinal	1.9/9.6	4.0/10.4
	Transverse	1.7/9.8	3.6/10.4
$HVSR_{entire}$	Longitudinal	1.9/*	3.9/10.6
	Transverse	1.7/10	3.5/10.9
Crest/Downstream ratio	Longitudinal	1.9/*	NA
	Transverse	2.2/*	NA
Crest/Abutment ratio	Longitudinal	2.2/*	4.0/*
	Transverse	2.0/*	4.0/*

Note: Fundamental vibration frequency/ Second mode of vibration, *no clear peak.

Figures 15a and b present a comparison of first mode frequency from HVSR results using S-wave versus entire motion in longitudinal and transverse directions for dams. As can be inferred from the figure, for the selected dam location HVSR result at crest sensors using either S-wave or entire motion resulted in similar first mode frequency peaks.

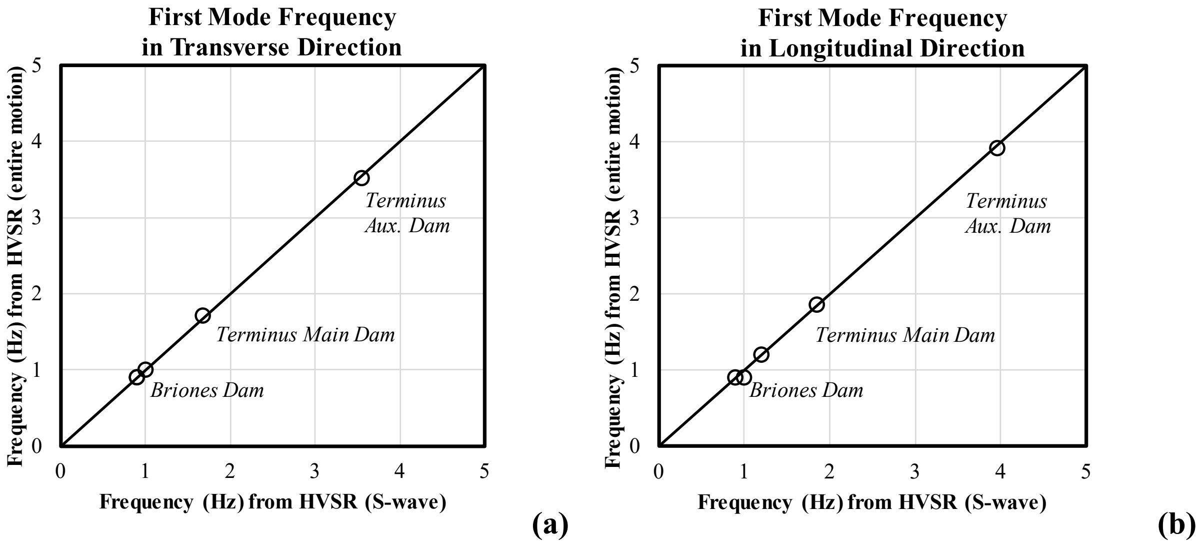


Figure 15. Comparison of first mode frequency from HVSR results using S-wave versus entire motion in a) longitudinal and b) transverse directions for dams.

Figures 16a and b present a comparison of first mode frequency from HVSR results using S-wave versus crest to abutment ratio in longitudinal and transverse directions for dams. As can be inferred from the figure, for the selected dam location HVSR result and crest to abutment ratio resulted in similar first mode frequency peaks.

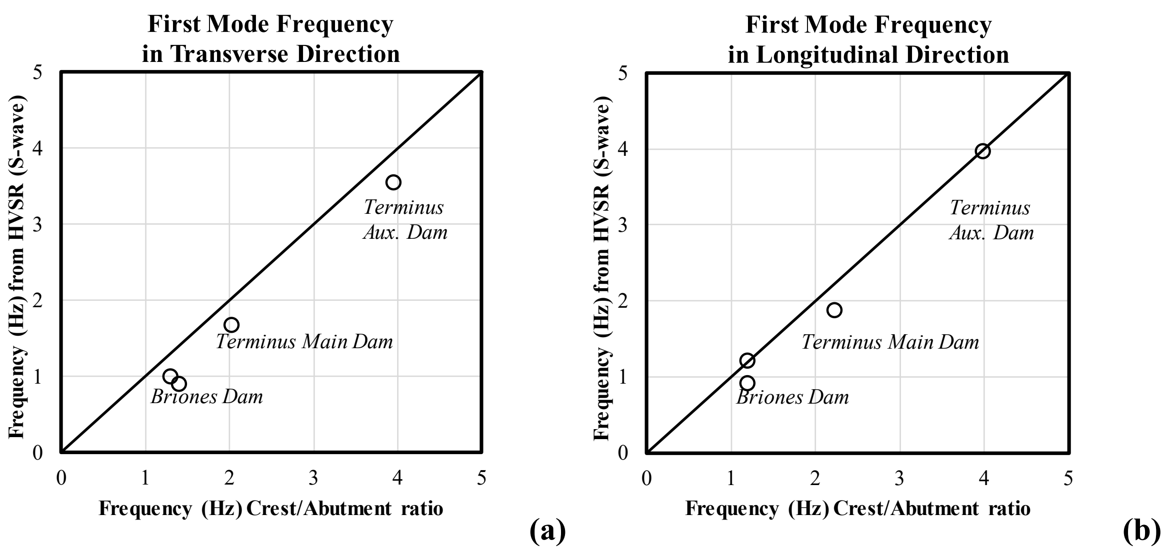


Figure 16. Comparison of first mode frequency from HVSR results using S-wave versus crest to abutment ratio in a) longitudinal and b) transverse directions for dams.

Gazetas (1987) showed that dams built in narrow canyons behave stiffer than those built in wide canyons. Their work provides recommendation of the stiffening effect of a narrow canyon on the fundamental natural as a function of L/H which is the aspect ratio. Figure 17 a-d presents L/H versus first and second mode frequency in transverse and longitudinal directions for Briones and Terminus dams along with data from Hwang et al (2008), Verret and LeBoeuf

(2021), Zimmaro and Ausilio (2020). Hwang et al (2008) studied the ratio of the Fourier amplitude spectrum and the response spectrum of the records from the crest to the downhole analyzing more than 30 events at each dam. The result of fundamental frequency of 5 dams with different aspect ratio in longitudinal and transverse directions are presented. Verret and LeBoeuf (2021) studied the vibration characteristics of Farneto del Principe Dam by various methods (e.g ambient noise measurements, shear beam methods, numerical analysis, analyzing recorded earthquake motion). Lastly, Zimmaro and Ausilio (2020) studied the vibration characteristics of Farneto del Principe Dam by performing finite element analysis and compare their results with other methods (e.g. shear beam method, etc.).

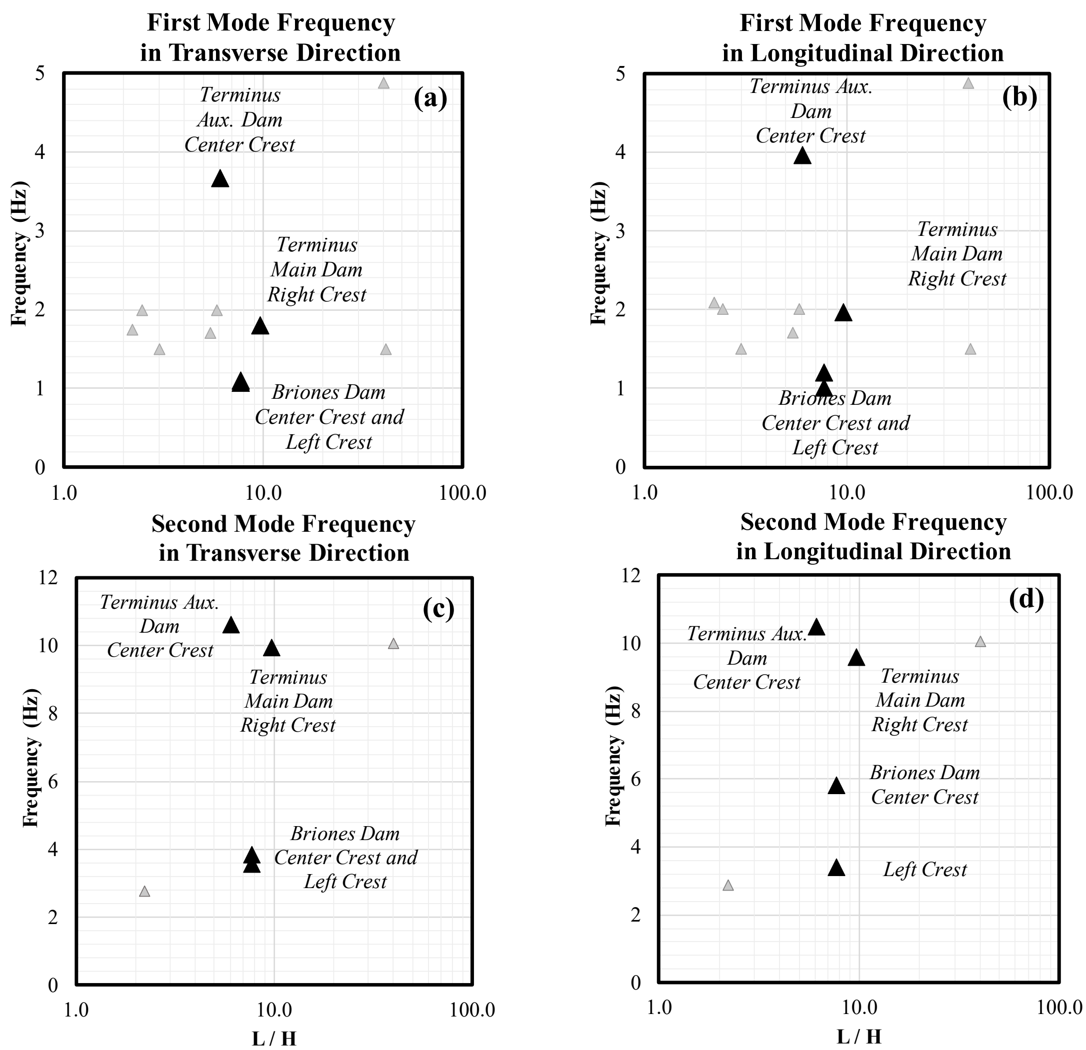


Figure 17. Summary of L/H versus frequency for selected dams in this study along with data from Hwang et al (2008), Verret and LeBoeuf (2021), Zimmaro and Ausilio (2020) a) first mode in transverse direction, b) first mode in longitudinal direction, c) second mode in transverse direction, d) second mode in longitudinal direction.

It can be concluded that the scatter in Figure 17 is wide as the first and second mode of the dams are examined for different aspect ratios. The vibration characteristics of dams (their natural periods and modal shapes) are affected by various factors which can be the reason behind the large scatter. The effect of canyon geometry, dam height and crest length, aspect ratio (L/H), the inclination of the two sloping faces, inhomogeneous dam materials, shear modulus and damping properties of dam material, the stiffness characteristics of the foundation materials, dam-reservoir interaction, level of nonlinearity under earthquake loading, directional effects (different vibration modes in upstream-downstream and longitudinal direction) are the factors that control the dynamic behavior of dams. The earthquake recordings that are used in this paper having peak accelerations less than 0.20g hence provides the assessment of fundamental behavior of dams. However, the dynamic analysis of dams requires a good understanding of the in-situ conditions and information on dam and foundation materials which is lacking for Briones and Terminus Dams. Although some of the aspects are still investigated, the comparison of first mode (fundamental) and second mode frequencies derived analyzing the low intensity events using HVSR and crest to abutment ratio provides comparable and promising results to evaluate the dynamic behavior of dams with simple methods. The effect of aspect ratio and other parameters on first and second mode frequency are currently studied for additional case histories and conclusions will be the scope of a future study.

Conclusions

The availability of the earthquake recordings at Briones and Terminus Dam provides an opportunity to assess the dynamic characteristics of the dam. Several different approaches were studied to assess the first and second mode frequency of the dam by comparing HVSRs. The comparison provides promising results to evaluate the dynamic behavior of dams with simple methods. Availability of a more detailed subsurface characterization as well as field measurements are needed before specific recommendations are formulated.

Acknowledgements

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References

1) Borcherdt, Roger D. (1970). Effects of local geology on ground motion near San Francisco Bay. *Bulletin of the Seismological Society of America* 60.1: 29-61.
2) Gazetas, G. (1987). Seismic response of earth dams: some recent developments. Soil dynamics and earthquake engineering, 6(1), 2-47.
3) Hassani, B., Yong, A., Atkinson, G. M., Feng, T., & Meng, L. (2019). Comparison of site dominant frequency from earthquake and microseismic data in California. *Bulletin of the Seismological Society of America*, 109(3), 1034-1040.
4) Hwang, J. H., Wu, C. P., & Chou, J. T. (2008). Motion characteristics of compacted earth dams under small earthquake excitations in Taiwan. In Geotechnical Earthquake Engineering and Soil Dynamics IV (pp. 1-12).
5) Kawase, H., Sánchez-Sesma, F. J., & Matsushima, S. (2011). The optimal use of horizontal-to-vertical spectral ratios of earthquake motions for velocity inversions based on diffuse-field theory for plane waves. *Bulletin of the Seismological Society of America*, 101(5), 2001-2014.
6) Kishida, T., Ktenidou, O. J., Darragh, R. B., & Walter, S. (2016). Semi-automated procedure for windowing time series and computing Fourier amplitude spectra (FAS) for the NGA-West2 database.
7) Konno, K. and Ohmachi, T., (1998). Ground-motion characteristics estimated from spectral

ratio between horizontal and vertical components of microtremor, *Bull. seism. Soc. Am.*, 88, 228–241.

8) Ktenidou, O. J., Chávez-García, F. J., Raptakis, D., & Pitilakis, K. D. (2015). Directional dependence of site effects observed near a basin edge at Aegion, Greece. *Bulletin of Earthquake Engineering,* 14, 623-645.
9) Lermo, J., and Chávez-García, F. J. (1993). Site effect evaluation using spectral ratios with only one station. *Bull. of the seismological society of America*, 83(5), 1574-1594.
10) Nakamura, Y., (1989), "A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface", *QR of Railway Technical Research Institute*, Vol 30, pp. 25-33.
11) Nakamura, Y., (1996). Real-time information systems for hazards mitigation, *Proceedings of the 11th World Conference on Earthquake Engineering*, Acapulco, Mexico.
12) Nakamura, Y., (2000). Clear identification of fundamental idea of Nakamura's technique and its applications, *Proceedings of the 12th World Conference on Earthquake Engineering,* Auckland, New Zealand.
13) Nogoshi, M. and Igarashi, T. (1970). On the propagation characteristics of microtremors. *J. Seism. Soc.* Japan 23, 264-280 (in Japanese with English abstract).
14) Nogoshi, M. and Igarashi, T. (1971). On the amplitude characteristics of microtremors. *J. Seism. Soc*. Japan. 24, 24-40 (in Japanese with English abstract).
15) Verret, D., & LeBoeuf, D. (2022). Dynamic characteristics assessment of the Denis-Perron dam (SM-3) based on ambient noise measurements. Earthquake Engineering & Structural Dynamics, 51(3), 569-587
16) Zhu, C., Cotton, F., & Pilz, M. (2020). Detecting site resonant frequency using HVSR: Fourier versus response spectrum and the first versus the highest peak frequency. *Bull. of the Seismological Society of America*, 110(2), 427-440.
17) Zimmaro, P., & Ausilio, E. (2020). Numerical evaluation of natural periods and mode shapes of earth dams for probabilistic seismic hazard analysis applications. Geosciences, 10(12), 499.