

## Site Effect Evaluation at Earth Dams in California Using the HVSR and SSR Method Based on Earthquake Records

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**ABSTRACT:** Analyzing the dynamic response of dams is a complex yet critical subject of geotechnical engineering. Engineers often rely on simplified methodologies derived from key case histories due to the challenges associated with numerical analyses, which demand extensive computational resources and precise characterization of soil properties. Observations from real-world case studies, however, offer quick and valuable insights into the complicated seismic behavior of dams. A key parameter in understanding the seismic response of dams is their first-mode fundamental frequency (or period). This study focuses on the seismic performance of earth dams in California, analyzing their vibration characteristics following seismic events. The analysis utilizes data from 177 strong ground motion recordings at 18 dams, sourced from the Center for Engineering Strong Motion Data (CESMD) and the California Strong Motion Instrumentation Program (CSMIP). Two key methods are employed: the Horizontal-to-Vertical Spectral Ratio (HVSR) and the Standard Spectral Ratio (SSR), which are calculated using earthquake recordings collected at crest and reference sensors. The fundamental frequencies ( $f_1$ ) of the dams are determined at different locations of the dams (e.g., center crest, left crest, etc.). The study provides a comprehensive assessment of various factors influencing seismic response, including differences in frequency peaks, dam geometry, canyon shape effects, directional impacts, sensor placement, and earthquake intensity levels. This database presents a systematic evaluation of earth dams in California, studying different methods using actual earthquake recordings. The promising initial findings highlight the potential of leveraging recorded data for analyzing dam behavior, providing a valuable foundation for future studies and advancing the understanding of the seismic response of earth dams.

**KEYWORDS:** Earth dams, Horizontal-to-Vertical Spectral Ratio, Standard Spectral Ratio, Earthquake, Fundamental Frequency

### 1 INTRODUCTION

The seismic response of earth dams is admittedly rather complicated; therefore, advanced methods of dynamic analysis are needed to capture the actual behavior of dams under seismic conditions. Such methods and associated advanced constitutive models are available today. Still, they need to be further developed and validated against case studies to obtain reliable results for dam analysis and design. Various methods have been developed over the years, ranging from the simple numerical shear beam method to the sophisticated nonlinear coupled dynamic analysis. However, it is essential to note that as the methods become more refined and can capture more complex aspects that influence the seismic response of earth dams, such as nonlinear soil response, inhomogeneous dam material, 3-D topographical effects, and the reservoir-dam interaction during shaking, the analyses become computationally intensive.

When evaluating the seismic response of earth dams, the fundamental (first mode) frequency ( $f_1$ ) of the dam and other vibration modes (e.g.,  $f_2$ ,  $f_3$ ,  $f_4$ , etc.) are important parameters in understanding its dynamic behavior. These parameters can be assessed using analytical, empirical, and numerical methods. Among them, empirical methods enable the evaluation of real-world case histories and the study of the response of actual dams under different earthquake conditions, providing an advantage in assessing the effects of all the complex and contributing factors on the dynamic response of dams, as well as calibrating our design and analysis procedures. Additionally, from a forward-engineering point of view, empirical methods also provide a practical approach for a design engineer to evaluate the performance of existing dams or in the preliminary stages of a new design. Empirical approaches include field testing, such as full-scale vibration tests and the collection of microtremors, as well as the use of Horizontal-to-Vertical Spectral Ratio (HVSR) and Standard Spectral Ratio (SSR) methods based on recorded ground motions at the dam crest and

reference bedrock sensors, which will be the scope of this paper.

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 and is indicative of the site's resonant frequencies. The HVSR is the ratio between the Fourier amplitude spectra (FAS) of the horizontal and vertical components of microtremors, which was first introduced by Nogoshi and Igarashi (1970, 1971) and has been widely used following the study by Nakamura (1989, 1996, 2000). HVSR based on microtremors or earthquake records are used to investigate the different modes of vibrations of earth dams (e.g., Oner (1984), Abdel-Ghaffar and Scott (1981), Cetin et al. (2005), Ruiz and Pando (2011), Verret and LeBoeuf (2017), Correia et al. (2019), Pastén et al. (2023), Ilgac and Athanasopoulos-Zekkos (2022, 2023), Ilgac et al (2024) and Athanasopoulos-Zekkos and Ilgac (2024), Ilgac et al. (2025), etc.).

The standard spectral ratio (SSR) method was initially proposed by Borcherdt (1970) to study the amplification characteristics of sites (e.g., Lachet et al. (1996), Haghshenas et al. (2008), and Rong et al. (2017), etc.). In this method, the Fourier amplitude spectra ratio between the site of interest and a reference bedrock motion is calculated. SSR can also be used to investigate the dynamic behavior of dams when foundation records are available (e.g., Boulanger et al. (1995), Matsumoto et al. (2005), Hwang et al (2008), Mejia and Dawson (2008), Sasaki et al. (2015), Park and Kishida (2019), Ilgac and Athanasopoulos-Zekkos (2022, 2023), Ilgac et al (2024), Athanasopoulos-Zekkos and Ilgac (2024), Ilgac et al. (2025), etc.). However, foundation records are not always readily available. In instances like this, the ratio of the Fourier amplitude of the crest to that of the abutment, downstream, or toe records can be investigated to understand the frequency-amplification characteristics of dams. In this context, the crest records are indicative of the dam's seismic response, while the

downstream, toe, or abutment records are approximately representative of the free-field rock motions. This analysis helps in understanding how the dam interacts with seismic waves and how it influences the overall seismic response of the dam system. As discussed by Mejia and Dawson (2008), it's important to note that the concept of modes of vibration and natural frequencies is not strictly applicable to a nonlinear system. However, the term "natural frequencies" is commonly used to denote those frequencies at which the dam motions exhibit significant amplification compared to selected reference motions. Since the downstream bedrock motions are generally representative of the free-field motions near the dam site, they serve as a convenient choice for reference motions to identify the "natural frequencies" of vibration of the dam.

One of the pioneering efforts to document and collect the case histories of earth dams during earthquakes was presented by Gazetas (1987). In this study, Gazetas presented the historical development of the shear beam approach, which is an analytically derived set of equations based on simplified assumptions, such as the dam consisting of homogeneous materials or only horizontal lateral displacements occurring. Gazetas discussed some of these assumptions, tested their applicability, and provided improvements to shear beam methods, as necessary, such as the notable inclusion of canyon effects to account for the 3D behavior of the dams. He also compared the results of the shear beam method with those of finite element analyses, highlighting several differences. For example, in some cases, the fundamental frequency calculated with the shear beam method was higher than that obtained from finite element analysis for rockfill dams with soft cores. Additionally, the presence of a wide canyon could increase the fundamental frequency by 10–15%. The most significant disagreement was observed in flexible dams, where the shear beam method overestimated crest peak acceleration by up to 50%. Nevertheless, Gazetas presented 12 actual earth dams from different parts of the world, and their recommended model was tested, integrating a limited number of earthquake recordings and full-scale vibration test data to validate analytical models; however, the study served as the pioneering work in understanding the seismic response of dams and bringing lessons learned from actual dams.

The documentation of individual case histories over the past 40 years has significantly contributed to the study of the seismic response of dams; however, such studies remain limited in scope. Some investigations present excellent examples of field vibration tests or sophisticated numerical analyses, examining, for example, how reservoir interactions influence dam responses during seismic events. These studies emphasize the importance of three-dimensional modeling in accurately capturing the coupled dynamics of the water-dam-foundation system. While single-case analyses provide valuable and detailed insights, they are insufficient for drawing generalized conclusions across the full range of dam geometries, materials, and site conditions.

A more recent and comprehensive study by Park and Kishida (2019) systematically evaluated 190 seismic records from the crests and foundations of 60 dams during 54 earthquakes. Their analysis focused on calculating SSR using crest-to-foundation records, determining amplification factors and fundamental periods of the dams, and examining input motion characteristics such as Arias intensity and peak ground acceleration (PGA). The database of 60 dams is located in Japan, where reference foundation sensors were available for all dams, enabling the direct calculation of SSR; however, HVSR analysis was not applied in their work. In their study, the fundamental frequency of a dam was defined as the frequency corresponding to the highest amplitude peak frequency in the

SSR curve. The study involved low- to high-intensity ground motions ( $>0.2$  g), and the dams considered were constructed using modern equipment and compaction methods. Their results showed notable scatter in both frequency ranges and amplification levels at the dam crests. Nevertheless, this remains the only systematically assessed dam database of its kind known to us.

The purpose of this study is to expand the available case histories for assessing the seismic response of dams by utilizing ground motion recordings from earth dams in California, sourced from the Center for Engineering Strong Motion Data (CESMD) and California Strong Motion Instrumentation Program (CSMIP) database. The goal is to investigate the dynamic characteristics of these dams and to discuss the influencing parameters by providing a comprehensive presentation of the database, rather than a set of design recommendations, which will be the scope of a future paper. The collection of the available case histories is significant because it encompasses a wide variety of dam types, sizes, geometrical configurations, and instrumentation layouts. It also allows for the evaluation of different analysis methods, such as HVSR and SSR, and for the assessment of how factors like reference sensor selection, canyon shape, plan geometry, dam geometrical features, directionality effects, the definition of fundamental frequency, amplification levels, characteristics of input ground motions, dam material type, and sensor location at the crest influence the observed seismic response. By analyzing this dataset, we aim to document the observed seismic behavior of dams and identify the key factors that shape the dynamic response.

## 2 COMPILATION OF THE DATABASE

### 2.1 California Dams

As discussed in the introduction, the objective of this study is to assess the vibration characteristics of earth dams located in California. Figure 1 illustrates the geographical distribution of 40 dams located within the State of California. The comprehensive analysis of all dams occasionally proved challenges due to constraints such as the absence of earthquake recordings or insufficient information regarding the available sensors. In light of these challenges, we will present a condensed summary of 18 dams. The names of the dams, along with their GPS coordinates, are summarized in Table 1. A comprehensive list of all investigated dams, along with the reasons for excluding certain sites, can be found in Athanasopoulos-Zekkos and Ilgac (2024). That reference also provides detailed information on the dams' geometrical characteristics, including plan and cross-sectional shapes, geological conditions, sensor configurations, information on dam materials, and characteristics of the recorded ground motion data.



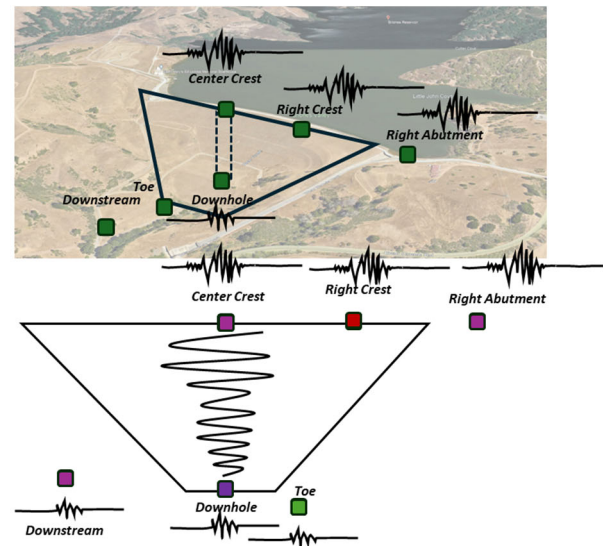
Figure 1. The location of the investigated earth dams located in California.

Table 1. The names of the dams along with the GPS locations

Dam #	Dam Name	Latitude	Longitude
1	Briones Dam	37.9135	-122.2092
3	Pomona - Puddingstone Dam	34.0906	-117.8092
4	Santa Felicia Dam	34.4612	-118.7517
5	Seven Oaks Dam	34.1174	-117.0971
6	Hayfork - Ruth Lake Dam	40.3686	-123.4339
7	San Miguel - San Antonio Dam	35.7986	-120.8851
8	Big Pine - Tinemaha Dam	37.052	-118.2215
9	Long Valley Dam	37.5879	-118.7065
10	Sierra Madre - Cogswell Dam	34.2449	-117.9653
13	Carbon Canyon Dam	33.9135	-117.84
14	Indian Creek Dam	38.752	-119.7794
15	Lake Success Dam	36.0616	-118.9229
19	Brea Dam	33.8898	-117.9251
21	Castaic Dam	34.5199	-118.6062
16a	Terminus Dam	36.4168	-119.0037
16b	Terminus Auxiliary Dam	36.4049	-119.0016
2a	Mathews Dam, Main Dam	33.8358	-117.4613
2b	Mathews Dam, Dike	33.8533	-117.4488

The ground motion recordings from sensors placed at various locations of the 18 dams are first downloaded from the Center for Engineering Strong Motion Data (CESMD), CSMIP database. Strong ground motion recordings were rotated to the transverse and longitudinal directions of the dam to study the upstream-downstream and longitudinal vibration characteristics of the dams. Then, all the recordings are examined using the procedure described by Kishida et al. (2016), which provides a semi-automated method for windowing time series (e.g., S-wave, P-wave) and computing FAS. The signal-to-noise ratio (SNR) is calculated for each earthquake record. With this approach, the usable frequency range for each record is estimated to eliminate the noise or any unwanted waves. At sensors located on the crest, HVSR is computed using each earthquake as a time window. Then SSR is calculated again at the sensor location on the crest using available reference sensors (left abutment, right abutment, downstream, toe, etc.) using earthquake records. The median HVSR and SSR curves are calculated, and resonant frequencies (e.g.,  $f_1, f_2, \dots$ ) are determined from the median curve. An illustrative sketch of the procedures described above is shown in Figure 1.

Given the variability in PGA levels, it is essential to consider that some motions may reach moderate-to-high intensity levels, potentially causing dams to exhibit nonlinear behavior. In contrast, others may remain at low-to-moderate intensity. Determining a threshold PGA value to distinguish events that cause nonlinearity is challenging, as it is unique to each dam's material properties and physical condition. In cases where dams experience high-intensity events, the observation of cracks indicates definite nonlinear behavior. These instances serve as landmark case studies, gathered from the literature. However, there may be cases where dams experience nonlinearity without significant strain and thus go unreported. Considering these complexities, we approached the problem by focusing on analyzing HVSR and SSR of individual earthquakes for events with intensities above 0.2 g at the crest. If the vibration characteristics differ significantly from low to moderate shaking levels, we examined them separately. On the other hand, for some dams, only high-intensity data was available, which inherently represents nonlinear conditions. Despite these complexities, we attempted to extract as much information as possible, occasionally studying individual events in detail.



$$HVSR = \frac{FAS(H_{tran}) \text{ or } FAS(H_{long})}{FAS(UP)}$$

$$SSR = \frac{FAS(\text{Center} - \text{Right} - \text{Left Crest})}{FAS(\text{Abutment, Toe or Downstream})}$$

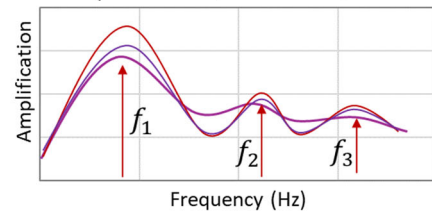


Figure 2. The illustrative sketch of the procedures implemented to determine the vibration characteristics of the dams.

## 2.2 Example Case History Processing

To illustrate how each dam is investigated, we present a case study of the Pomona (Puddingstone) dam, which is located in the San Gabriel Valley, Los Angeles, California (34.0906, -117.8092), and was built in 1928. The dam is an earth dam and serves the primary purpose of flood control. It stands at an elevation of 301 meters. The dam has a height of 45 m and a crest length of 331 m (CSMIP). In 1978, 15 accelerometers were positioned at the left abutment (Loc 1), the left crest (Loc 2), the center crest (Loc 3), the right abutment (Loc 5), and the downstream location (Loc 6). The dam was re-instrumented in 2009. Figure 3 shows the plan view of the dam and the installed accelerometers as provided by the CSMIP database. The accelerometers placed at the center crest and abutments are oriented in alignment with the dams' transverse and longitudinal directions.

The CSMIP database provides five earthquake recordings from Pomona Dam, featuring magnitudes ( $M_w$ ) ranging from 3.6 to 6.0. These are the Whittier Earthquake of October 1, 1987, the Pomona Earthquake of September 19, 2013, the La Habra Earthquake of March 28, 2014, and the La Verne Earthquake of August 28, 2018. Following the La Habra Earthquake on March 28, 2014, the peak acceleration (PGA) at Loc2 and Loc3 reached 0.16 and 0.23 g, respectively. These values suggest the potential for some nonlinear behaviors in response to this seismic event. However, it is observed that the remaining events were characterized by low-intensity levels, indicating that the dam likely did not exhibit nonlinear behavior during these events. When the individual recordings were

assessed, no distinct behavior was observed; hence, all the events were evaluated together. Figure 4 presents the analysis results at the center crest (Loc3) in the longitudinal direction. Based on the analysis, the following observations are made: All methods, including HVSR (Figure 4a) and SSR, using crest to downstream ratios (Figure 4b), crest to right abutment (Figure 4c), and crest to left abutment (Figure 4d) in longitudinal directions at the center crest (Loc3) indicate a peak around 2.5 Hz at the center crest in the longitudinal direction. However, HVSR also exhibits a first peak at 0.76 Hz, whereas the crest-to-downstream ratio shows a peak at 1.74 Hz. Similarly, calculations are performed for the transverse directions, and all methods exhibit a peak at 1.9-2.1 Hz, while HVSR again shows first-mode peaks around 0.75 Hz at the center crest. When the same calculations are performed at the sensor located on the left crest, HVSR shows the highest amplitude peak around 1.8 Hz, whereas a first amplitude peak is still present at 0.77 Hz. In contrast, SSR shows a shifted frequency at 4.6 and 5.2 Hz using the right and left abutment sensors, respectively. In all analyses, amplification was about 5 to 10 at the crest of Pomona Dam. As discussed above, the sensor location and the definition of the peak both affect the determination of the fundamental frequency.

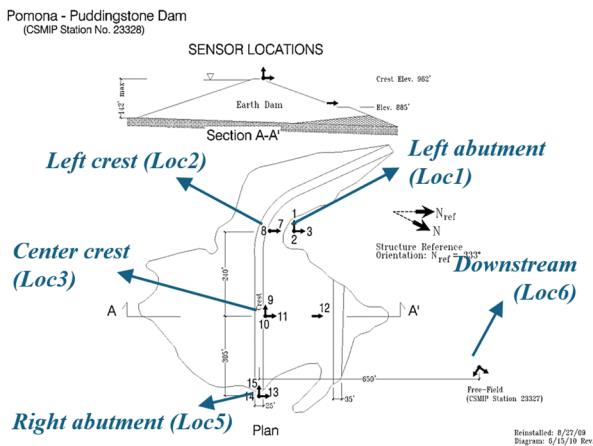


Figure 3. Plan view of Pomona-Puddingstone Dam (Pomona-Puddingstone Dam, CGS - CSMIP Station 23328) (after CSMIP database)

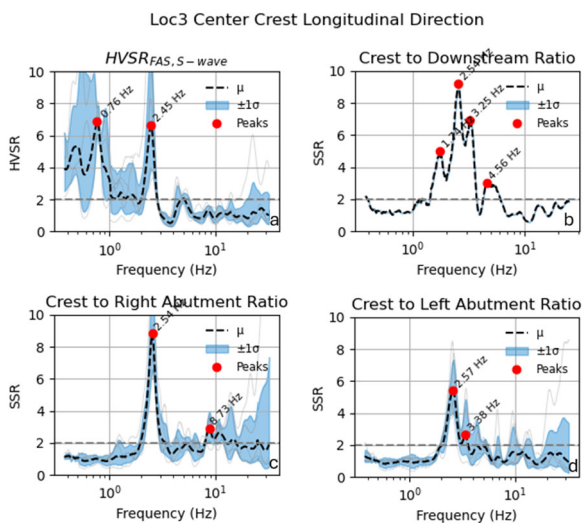


Figure 4. a) HVSR curves using FAS S-wave, and SSR curves using b) crest to downstream ratios, c) crest to right abutment, and d) crest to left abutment in longitudinal directions at the center crest (Loc3).

### 3 OVERVIEW OF THE CALIFORNIA DAM DATASET

Processing the database reveals several challenges due to the nature of field data. Nonetheless, the database serves as a large-scale, real-world experiment. In this paper, we aim to document these challenges and discuss the methodological choices required for data analysis.

The following sections highlight factors that must be considered, as these parameters and decisions directly influence the results. Each factor was examined individually; however, taken together, they contribute to the overall variability. For instance, when discussing methodological differences such as choosing between SSR and HVSR, the effect of sensor location also plays a role in the observed variations. Although fully separating these influences is not straightforward, we attempt to illustrate their impact by providing a focused view into the dataset.

#### 3.1 Different empirical approaches:

Two primary methods, HVSR and SSR, were employed to evaluate the frequency-amplification characteristics of dams. For HVSR, previous studies have shown that it can be calculated from either Fourier Amplitude Spectra (FAS) or response spectra, and it may be interpreted using different wave portions (e.g., the entire earthquake record versus only the intense S-wave portion). In this study, HVSR results are presented using FAS and the S-wave portion, so as not to extend the discussion further, and also since S-wave based HVSR is considered to capture amplitude response better. SSR was also calculated using different reference sensors (e.g., abutment, toe, etc.). Figure 5 presents a comparison of the two methods. At each sensor on the crest, both HVSR and SSR were calculated for each event, and the highest amplitude peak frequency ( $f_{peak}$ ) was identified from the median curve. These values were then plotted against dam height. As can be interpreted from the figure, SSR generally yielded higher frequency values compared to HVSR. It should be noted that the dataset presented in Figure 5 includes sensors distributed across the entire crest (e.g., center, left crest, and right crest) or dams having different canyon shapes, etc. As pointed out before, the comparison of SSR and HVSR here is not completely due to different methodological choices, but they are affected by various parameters. However, Figure 5 and database processing revealed some observations. When sensors were located closer to the abutments, as illustrated in the Pomona Dam case history, SSR occasionally produced shifted higher frequencies, whereas HVSR sometimes indicated additional low-frequency peaks. The underlying reasons for these discrepancies are likely associated with differences in wave propagation paths, boundary conditions near the abutments, and the varying sensitivity of each method to site and sensor location effects. To further investigate these methodological differences, a field testing campaign is currently underway. However, as a final note, it is encouraging that for most of the dataset these two fundamentally different methods, SSR and HVSR, yield broadly similar results.

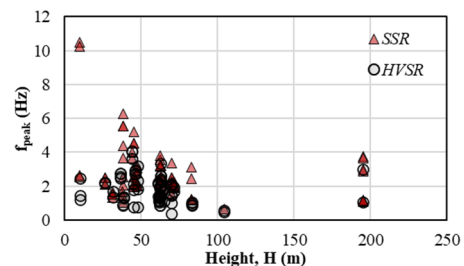


Figure 5. Dam height versus  $f_{peak}$  derived from SSR and HVSR.

### 3.2 SSR without foundation records:

Unlike Park and Kishida (2019), our database generally lacks direct foundation motion recordings. Only one dam in our study includes a downhole array within the dam body. To address this limitation, we use available sensors at locations such as the dam toe, downstream, or abutments as reference sites. Although the exact soil and rock conditions at these sites are not always known, the sensors are assumed to approximate reference rock conditions relative to the dam crest, where the dam structure significantly influences ground motions. Due to space limitations, not all parameter effects can be presented here. Nevertheless, during database processing, we observed that selecting reference sensors in free-field positions, such as downstream sites, tends to reduce the topographical effects that are more pronounced when using sensors near the abutments.

### 3.3 Directionality of seismic response:

Differences between longitudinal and transverse dam responses are evaluated to determine the effects of the dam on upstream, downstream, and longitudinal directions. As shown in Figure 6, very similar frequency values were observed in both directions. However, closer inspection of individual dams revealed notable differences between the longitudinal and transverse responses. These variations appear to be linked to each dam's unique characteristics, such as canyon geometry and material properties. Therefore, directionality should be examined further in conjunction with other structural and site-specific properties of the dams.

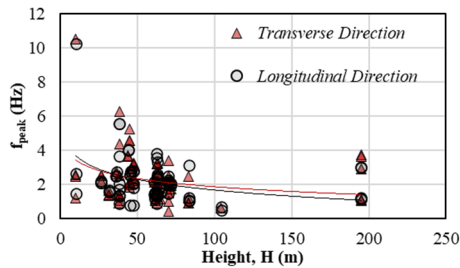


Figure 6. Dam height versus  $f_{\text{peak}}$  in longitudinal and transverse directions

### 3.4 Amplifications:

One of the most important parameters for the design procedures of a dam is the evaluation of amplification at the dam crest. Figure 7 presents the relationship between the highest amplitude peak ( $A_{\text{peak}}$ ) and dam height. As has been emphasized repeatedly, dam height alone is not the sole controlling parameter for amplification at the crest; for example, it is a function of intensity level (e.g., PGA) and material and foundation properties. Nevertheless, a key takeaway from the figure is that both HVSR and SSR methods yield broadly similar amplification levels. The observed variation, however, is large, ranging from approximately 2 to 30, indicating the critical importance of further studies.

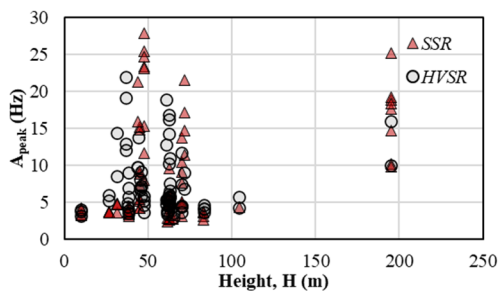


Figure 7. Dam height versus  $A_{\text{peak}}$  derived from SSR and HVSR.

### 3.5 Identification of fundamental frequency:

There is an ongoing debate regarding whether the fundamental mode frequency corresponds to the highest amplitude peak or to the first frequency peak in free-field sites. The same question arises when evaluating spectral peaks for dams. Figure 8 presents  $f_{\text{peak}}$  (Fig. 8a) and  $f_0$  (Fig. 8b) plotted against dam height. As shown in the figures,  $f_0$  values are smaller than  $f_{\text{peak}}$  for some dams, while in other cases the two coincide. When  $f_0$  is considered, HVSR occasionally produces unrealistically low frequency values. Currently, our efforts are focused on understanding the origin of these differences and accurately identifying which peak represents the first mode frequency of a dam.

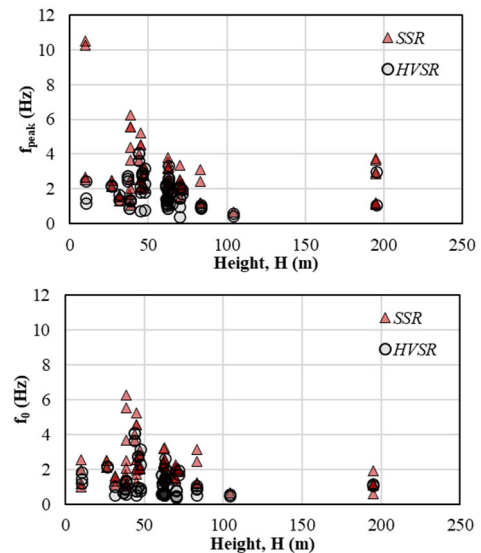


Figure 8. Dam height versus a)  $f_{\text{peak}}$  and b)  $f_0$ .

Several factors influence the dynamic response of dams and the interpretation of fundamental frequencies and crest amplifications. The level of nonlinearity is particularly important: under low to moderate shaking, dam materials and foundation soils may behave elastically, whereas stronger motions can induce nonlinear soil behavior that alters both frequencies and amplification levels. Material properties are also critical, with earthfill and rockfill dams exhibiting distinct dynamic behaviors. Geometrical features such as dam height, length, and aspect ratio ( $L/H$ ) show correlations with vibration characteristics. At the same time, canyon geometry, plan view configuration, and slope geometry contribute further variability and warrant detailed investigation. Input motion characteristics (e.g., PGA, predominant frequency of the input motion, Arias intensity, source distance, etc.) strongly affect  $f_1$  and amplification levels, underscoring the need for event-based analyses. Sensor location is another key consideration: crest sensors near abutments or shallow zones may capture local boundary effects rather than overall dam response, and thus should be analyzed separately. Reservoir water levels during earthquakes can also significantly influence dam response, yet data on this parameter remain limited. Likewise, shear-wave velocity ( $V_s$ ), a fundamental input for interpreting and modeling dynamic behavior, was unavailable in most cases. Our current database, which compiles many of these parameters, is documented in Athanasopoulos-Zekkos and Ilgac (2024). Expanding the dataset with additional seismic events is essential to strengthen these observations and improve the understanding of dam seismic response. To this end, we plan field measurements, such as those presented by Ilgac et al. (2025) for Briones Dam, and complementary numerical modeling.

## 4 CONCLUSIONS

While the initial results obtained using recorded motions provide valuable insights, further investigation and additional analyses are necessary to fully understand the vibration characteristics of dams before making strict recommendations on how to calculate these fundamental frequencies and associated amplifications using recorded motions. However, this database represents the first systematic evaluation known to the authors that studies different methods using actual earthquake recordings on several dams featuring various geometrical features and material types. The promising initial findings underscore the potential of using recorded data for such analyses. Broadening the database through such efforts will provide critical insights and make meaningful contributions to the field.

## 5 DATA AVAILABILITY

The authors acknowledge accessing strong-motion data through the Center for Engineering Strong Motion Data (CESMD), last visited on 23.08.2022. The networks or agencies providing the data used in this report are the California Strong Motion Instrumentation Program (CSMIP) and the USGS National Strong Motion Project (NSMP) (CGS & USGS, 2005; <https://www.strongmotioncenter.org/>).

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## 8 REFERENCES

- Athanasopoulos-Zekkos, A., & Ilgac, M. (2024). Using CSMIP data to derive reliable dynamic response parameters for earth dams in California (Research Project Final Report, approved).
- Borcherdt, R. D. (1970). Effects of local geology on ground motion near San Francisco Bay. *Bulletin of the Seismological Society of America*, 60(1), 29-61.
- California Geological Survey and U.S. Geological Survey (2005). Center for Engineering Strong Motion Data (CESMD). U.S. Geological Survey <https://doi.org/10.5066/P13HTZQS>
- Boulanger, R. W., Bray, J. D., Merry, S. M., & Mejia, L. H. (1995). Three-dimensional dynamic response analyses of Cogswell Dam. *Canadian geotechnical journal*, 32(3), 452-464.
- Cetin, K. O., Isik, N. S., Batmaz, S., & Karabiber, S. (2005). A comparative study on the actual and estimated seismic response of Kiralkizi Dam in Turkey. *Journal of Earthquake Engineering*, 9(04), 445-460.
- Correia, N., & Pasten, C. (2019). Using Seismic Records to Determine the Predominant Vibration Frequency of a Tailings Dam Embankment: First Results. In 6th International Seminar on Tailings Management, Tailings.
- Haghshenas, E., P. Y. Bard, N. Theodulidis, & SESAME WP04 Team (2008). Empirical evaluation of microtremor H/V spectral ratio, *Bull. Earthq. Eng.* 6, 75-108.
- 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).
- Gazetas, G. (1981). Longitudinal vibrations of embankment Gazetas, G. (1987), 'Seismic response of earth dams: some recent developments', *Soil Dynamics and Earthquake Engineering* 6(1), 3-47.
- Ilgac, M., & Athanasopoulos-Zekkos, A. (2022). Using CSMIP data to derive reliable values of dynamic response parameters for earth dams in California. In *Proceedings of the SMIP22 (Strong Motion Instrumentation Program) Seminar on Utilization of Strong-Motion Data*.
- Ilgac, M., & Athanasopoulos-Zekkos, A. (2023). Assessment of vibration characteristics of Briones and Terminus Dams using earthquake recordings. In *Proceedings of the SMIP23 (Strong Motion Instrumentation Program) Seminar on Utilization of Strong-Motion Data*.
- Ilgac, M., Athanasopoulos-Zekkos, A., & Ktenidou, O. (2024). Estimation of dam vibration characteristics from ground motion records— An illustrative example: Briones Dam, California. In *Proceedings of the 8th International Conference on Earthquake Geotechnical Engineering* (8 ICEGE), Osaka, Japan.
- Ilgac, M., Athanasopoulos-Zekkos, A., Nweke, C. C., Ktenidou, O.-J., Peterson, K., & Kayen, R. E. (2025). Embankment vibration characteristics using ground motion records and ambient noise measurements, Briones Dam, California. *Soils and Foundations*, 65(4), 101664. <https://doi.org/10.1016/j.sandf.2025.101664>
- Lachet, C., D. Hatzfeld, P. Y. Bard, N. Theodulidis, C. Papaioannou, & A. Savvaidis (1996). Site effects and microzonation in the city of Thessaloniki (Greece). Comparison of different approaches, *Bull. Seismol. Soc. Am.* 86, 1692-1703
- Lermo, J., and Chávez-García, F. J. (1993), "Site effect evaluation using spectral ratios with only one station", *Bulletin of the Seismological Society of America*
- Mejia, L. and Dawson, E. (2008) Analysis of Seismic Response of Seven Oaks Dam, Data Utilization Report, CSMIP, California Dept of Conservation, Division of Mines and Geology
- Matsumoto, N. (2010). The recent earthquakes and dam safety in Japan. na.
- 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
- Nakamura, Y., 1996. Real-time information systems for hazards mitigation, *Proceedings of the 11th World Conference on Earthquake Engineering*, Acapulco, Mexico.
- 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.
- Nogoshi, M. and Igarashi, T. (1970). On the propagation characteristics of microtremors. *J. Seism. Soc. Japan* 23, 264-280(in Japanese with English abstract).
- Nogoshi, M. and Igarashi, T. (1971). On the amplitude characteristics of microtremors. *J. Seism. Soc. Japan*. 24, 24-40(in Japanese with English abstract).
- Oner, M. (1984). Estimation of the fundamental period of large earthfill and rockfill dams. *Soils and foundations*, 24(4), 1-10.
- Park, D., & Kishida, T. (2019). Seismic response of embankment dams based on recorded strong-motion data in Japan. *Earthquake Spectra*, 35(2), 955-976.
- Rong, M., Fu, L. Y., Wang, Z., Li, X., Carpenter, N. S., Woolery, E. W., & Lyu, Y. (2017). On the amplitude discrepancy of HVSR and site amplification from strong-motion observations. *Bulletin of the Seismological Society of America*, 107(6), 2873-2884.
- Ruiz, E., & Pando, M. (2011). Use of Ambient Vibration Measurements to Infer Dynamic Properties of Poorly Characterized Old Earth Dams—A Case History from Puerto Rico. In *Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 1842-1851).
- Sasaki, T., Ohmachi, T., & Matsumoto, N. (2018). Analysis on acceleration data of dams collected by JCOLD. In *Validation of Dynamic Analyses of Dams and Their Equipment* (pp. 3-30). CRC Press.
- Verret, D., LeBœuf, D., & Péroquin, É. (2021). Site effects of the Denis-Perron dam (SM-3): A case study in Eastern North America. *Earthquake Spectra*, 37(1\_suppl), 1602-1625.