USING CSMIP DATA TO DERIVE RELIABLE DYNAMIC RESPONSE PARAMETERS FOR EARTH DAMS IN CALIFORNIA –

An Illustrative Example

Ilgac, Makbule[1] and Athanasopoulos-Zekkos, Adda[2]

[1] Post-Doctoral Researcher, University of California, Berkeley, [2] Associate Professor, University of California, Berkeley

Abstract

The purpose of this paper is to improve understanding of the seismic response of earth dams and create a framework for strong-motion data processing that can lead to improvement in the seismic design code provisions and practices for earth dams. CSMIP earthquake recordings from different locations on the dams are assessed to develop Horizontal to Vertical spectral ratios to assess the fundamental resonance frequency of the sites and amplification factors as well as stiffness for the dam and foundation materials which are estimated directly from the recorded motions. The results for Seven Oaks Dam are presented as an illustrative example.

Introduction

Earthen dams play a very important role in flood defense, while many are also used for water supply, irrigation, power generation, transportation, and sediment retention among other roles. The state is also heavily reliant on the nearly 1500 dams, the vast majority of which are earthen, that play a crucial role in California's water management. The potential dam failure modes related to earthquakes and the associated seismic hazard of ground shaking are often the driving design criteria for new dams in earthquake-prone regions, and the primary concern when evaluating the safety of many existing dams. California is an active tectonic region characterized by high seismic hazards. There is a unique opportunity to utilize the CSMIP network's strong motion data to improve our understanding of the dynamic response of earth dams in California on a broader scale and beyond limited individual case studies, and therefore make our seismic hazard assessment more rigorous. The FEMA guidelines for Earthquake Analysis and Design of Dams (FEMA, 2005) do provide a general framework for how to approach this and minimum requirements, however, leave many aspects to the judgment of the engineer. The US Bureau of Reclamation provides more detail in the recent Design Standards for Embankment Dams (USBR, 2015); however, the main emphasis is on liquefaction assessment and permanent slope displacements, and not on best practices for site response and dynamic analyses.

Our objective in this proposed study is to improve our understanding of the seismic response of earth dams and create a framework for strong-motion data processing that can lead to improvement in the seismic design code provisions and practices with respect to earth dams. Specifically, it is proposed to use CSMIP earthquake recordings from different locations on the dams (toe, crest, abutment, etc.) to develop Horizontal to Vertical (H/V) spectral ratios (Nakamura, 1989) for each dam location. Stiffness (G_{max}) and damping parameters (d) for the dam and foundation materials will be estimated directly from the recorded motions and simplified site response analyses will also be conducted to compare the computed amplification with the one observed in the recordings.

There are currently no explicit guidelines focusing on the evaluation of the dynamic response of dams. Engineers rely on published works in the literature for simplified procedures and guidance on analyzing the dynamic response of earth dams, and in doing so, often must qualitatively assess the site's fundamental period, the dynamic properties of the dam materials (e.g., G_{max}) and any expected amplification (site) effects. This literature also typically focuses on landmark cases of dam response following large earthquakes but does not provide a consistent framework that can be applied to a wide range of earth dams (small to large and in different geologic settings). It is aimed to first-time leverage a large dataset available through CSMIP to explore the general applicability of the proposed technique for a range of dam sites. Within the confines of this study, an illustrative dam site Seven Oaks Dam is selected to present the methodology to assess the HVSR curves to determine the resonance frequency of the site and amplification factors, and dynamic properties of the dam materials (e.g., G_{max}). A comparison of the results with 1-D equivalent linear site response analysis will be shown.

In subsequent analysis, this approach will be applied to more than 40 dam sites in California to understand the dynamic response of dams which is not the scope of this paper.

Background Information on Dynamic Response of Earth Dams

The seismic response of earth dams is admittedly rather complicated. Therefore, advanced dynamic analysis methods need to be employed to capture dams' actual behavior 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. For example, Mejia and Dawson (2008) showed that when analyzing the dynamic response of the Seven Oaks Dam as part of a CSMIP Data utilization study, considerable uncertainties are associated with the assumed analysis inputs. The main sources of uncertainty appear to lie in the assumed seismic wave field at the site during the earthquakes, and the properties of the embankment and foundation materials. The uncertainties in the shear moduli of the embankment materials at small strains would be considerably reduced through in-situ measurements of the shear and compression wave velocities of the embankment materials.

The vibrations of earth dams in the upstream-downstream direction were initially investigated by Ambraseys (1960a) using the shear beam method. Dakoulas and Gazetas (1985) studied the crest amplification of a dam for various damping ratios and showed its dependency on the dam's fundamental period. It has generally been shown that dams built in narrow deep canyons behave in a stiffer manner than dams built in wider canyons. The stiffening effect of narrow canyon results in smaller natural periods. The effect of the three-dimensional geometry of the dam-canyon system was firstly studied in the 1950s by Hatanaka (1952) and Ambraseys (1960b). These authors concluded that canyon effects are negligible for dams in rectangular canyons with dam length-to-height ratios, $L/H > 4$. Later in-depth investigations include the work of Dakoulas and Gazetas (1986, 1987) using the shear beam method and Mejia and Seed (1983) using the finite element method.

With respect to inhomogeneity in dams, previous studies have shown that inhomogeneity affects the dynamic response of earth dams. It has been reported (e.g., Gazetas, 1987) that the effects of inhomogeneity are less pronounced if nonlinear material behavior is considered.

The methods for analyzing the dynamic response of earth dams fall into three main categories: (a) pseudo-static methods to assess the stability of the earth dam (i.e., the dam slope), (b) sliding block analysis methods which calculate the permanent displacements and (c) methods evaluating the dynamic response of the whole dam structure, such as the shear beam approach. However, advanced numerical techniques, such as the finite element method have the capacity to satisfy all the analysis objectives: stability, displacements, and dynamic response. Numerical methods have been formulated to model the nonlinear material behavior of the dam materials, which cannot be calculated analytically. 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 are able to capture more aspects of the soil's response, the nonlinearity as well as the reservoir-dam interaction during shaking, the analyses become computationally intensive (and by extension, time-consuming). As a result, in practice a much smaller number of input ground motions are being used for the dynamic analyses, not allowing for the investigation of the impact of the input ground motion parameters.

Site effects associated with local geologic conditions constitute an important part of any seismic hazard assessment. Many examples of catastrophic consequences of earthquakes have demonstrated the importance of reliable analysis procedures and techniques in earthquake hazard assessment and in earthquake risk mitigation strategies. The fundamental period of the site, as well as the dam itself, are parameters that to a large degree control the dynamic response of the earth dam. The H/V spectral ratio method is an experimental technique to evaluate some characteristics of soft-sedimentary (soil) deposits. Due to its relative simplicity, both for the survey and analysis, the H/V technique has been frequently adopted in seismic microzonation investigations and has shown to be useful to estimate the fundamental period of soil deposits. However, measurements and analysis should be performed with caution. The main recommended application of the H/V technique by SESAME (2000) is to map the fundamental period of the site and help constrain the geologic and geotechnical models used for numerical computations. In addition, this technique is also useful in calibrating site response studies at specific locations. The European research project SESAME (Contract. No. EVG1-CT-2000-00026) conducted some years ago, provides guidelines for data processing and interpretation.

The H/V spectral ratio (i.e., the ratio between the Fourier amplitude spectra of the horizontal and the vertical component of microtremors was first introduced by Nogoshi & Igarashi (1970 and 1971) and became more widespread by Nakamura (1989, 1996, 2000). These authors have pointed out the correlation between the H/V peak frequency and the fundamental resonance frequency of the site and proposed to use the H/V technique as an indicator of the subsurface conditions. Since then, a large number of experiments (Lermo & Chavez-Garcia 1993; Gitterman et al. 1996; Seekins et al. 1996; Fah et al. 2001) have shown that the H/V procedure can be successfully applied to identifying the fundamental resonance frequency of sedimentary deposits. These observations were supported by several theoretical 1-D investigations (Field & Jacob 1993; Lachet & Bard 1994; Lermo & Chavez-Garcia 1994; Wakamatsu & Yasui 1996; Tokeshi & Sugimura 1998), that have shown that noise synthetics computed using randomly distributed near-surface sources lead to H/V ratios that sharply peak around the fundamental S-wave frequency when the surface layer exhibits a sharp impedance contrast with the underlying stiffer formations. There is still ongoing research into the applicability of this technique to evaluating site amplification (Bard 1998; Bour et al. 1998; Mucciarelli 1998; Al Yuncha & Luzon 2000; Maresca et al. 2003; Rodriguez & Midorikawa 2003). If the shape of the H/V curves is controlled by the S-wave resonance within the sediments then both H/V peak frequency and amplitude may be directly related to the soil transfer function (in terms of fundamental resonance frequency and site amplification factor (Nakamura (1989, 2000. On the other hand, if the shape of the H/V curves is controlled by the polarization of fundamental Rayleigh waves (Lachet & Bard 1994; Kudo 1995; Bard 1998; Konno & Ohmachi 1998; Fah et al. 2001), then only an indirect correlation between the H/V peak amplitude and the site amplification may exist. Finally, combining H/V information with data from active source methods (SASW, MASW, etc.) provides additional constraints to the inversion problem needed for evaluating the shear wave velocity profile (V_s) (Wood et al. 2014).

The seismic recordings of vertical arrays of accelerometers have also been used for extracting shear stress-strain loops of soil which are then utilized for estimating the corresponding values of shear modulus, G, and damping, D, as a function of soil shear strain. The first applications of this technique have been reported by Abdel-Ghaffar and Scott (1979a, b), Lin and Chao (1990), Koga and Matsuo (1990), and Lin (1994). The first application of extracting shear stress-strain loops from the seismic recordings of the Superstition Hills 1987 earthquake at the Wildlife Refuge (Imperial County, California site) was made by Zeghal and Elgamal (1994) which forms the basis of the analysis discussed in this study.

Methodology

H/V spectral ratios will be used for evaluating the fundamental site period as well as the fundamental period of the dam. The effect of distance and depth of vibration source on the H/V ratios due to different earthquakes will also be investigated. Once the H/V ratios are determined, they can be used with near real-time generated shake maps, to predict locations of expected high-motion amplification and provide an immediate assessment of likely damage to the dam. This will be the first time this approach is implemented at the State level scale. This will allow for documentation of the accuracy of these methods depending on shaking intensity and dam characteristics, as well as assess the impact of the estimated fundamental site period on-site amplification.

The proposed research approach includes processing Ground Motion Recordings and calculations of H/V ratios. Firstly, all relevant recordings at the dam sites of interest work are collected and processed to develop Horizontal to Vertical (H/V or HVSR) spectral ratios for the dam location. Strong ground motion data is collected and band-filtered with the Butterworth filter to eliminate the low and high frequencies that are associated with noise and eventually earthquake-induced frequency levels will remain. The H/V spectral ratios will be used for evaluating the fundamental site period as well as the fundamental period of the dam. Lermo and Chavez-Garcia (1993) have shown that it is possible to identify a dominant period (i.e., resonance frequency) and local amplification using recordings from only one station if the site effects are due to simple geology (e.g., horizontal stratification). According to the method, records are transformed in the frequency domain, and smoothed, and the geometric mean of the horizontal components is divided by the vertical component. If there is a strong velocity contrast in the subsurface (e.g., an impedance ratio greater than ~2), a peak will be observed in the frequency-spectral ratio domain that will be equal to the fundamental site period. The effect of distance and depth of vibration source on the H/V ratios will be studied for the cases where recordings from multiple earthquakes are available. Once the H/V ratios are determined, they can potentially be used with near real-time generated shake maps, to predict locations of expected high-motion amplification and provide an immediate assessment of likely damage to the dam.

Our vision is to use the ground motion recordings at the earth dam sites that are part of the CSMIP database (and supplement them with a few more from the PEER NGA West 2 updated database) to develop such an approach. Specifically, our approach will aim to compute and analyze the H/V spectral ratios of recordings and investigate the resonance frequencies as well as the amplification characteristics of these sites. The procedure to calculate the resonance frequencies is summarized in Figure 1.

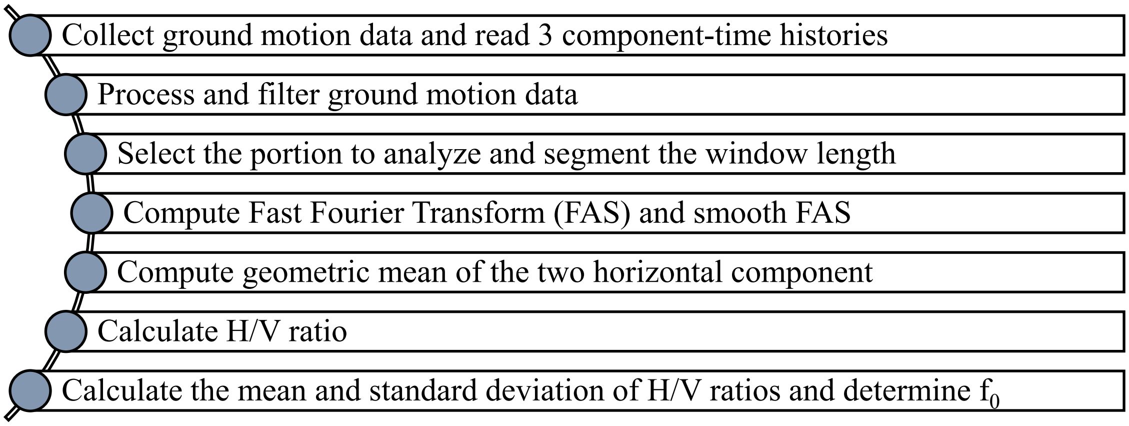


Figure 1. Flowchart of the procedure for calculating H/V ratios at strong ground motion stations.

The seismic recordings of vertical arrays of accelerometers will be used for extracting shear stress-strain loops of soil which are then utilized for estimating the corresponding values of shear modulus, G, and damping, D, as a function of soil shear strain following the procedure by Abdel-Ghaffar and Scott (1979a, b), Lin and Chao (1990), Koga and Matsuo (1990) and Lin (1994). The procedure to calculate stress-strain loops is summarized in Figure 2.

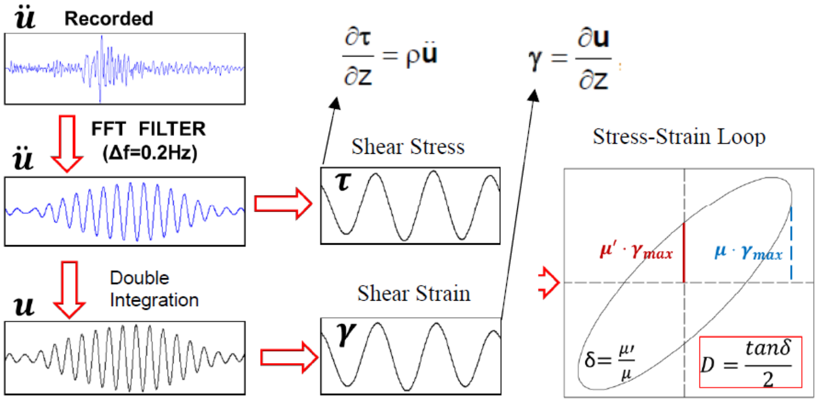


Figure 2. Overview of the steps used for developing the shear stress-strain loops from earthquake recordings

California Strong Ground Motion Network

Given the new recordings following some recent earthquakes in California (e.g., Ridgecrest sequence), and the upcoming updates to the CESMD database as presented during the 2019 annual COSMOS Technical Session (Haddadi, H., 2019), all relevant motions to our analyses in CESMD database is investigated. Figure 3 presents the location of the 40 dams in the State of California and Table 1 list these dams that we intend to include in future studies.

Figure 3. Map of the State of California with the locations of the dam sites that will be included in this study.

Table 1. Stations located at dams in the Center for Engineering Strong Motion Data (CESMD) Strong-Motion Database

Stations located at dams in the CESMD	
Anderson Dam	Los Gatos - Lenihan Dam
Big Pine - Tinemaha Dam	Martis Creek Dam
Bouquet Canyon Reservoir Dam No. 1	Monterey Park; Garvey Reservoir

Brea Dam	Murietta Hot Springs; Skinner Dam
Brea; Orange County Reservoir	New Hogan Dam
Briones Reservoir - Briones Dam	Palos Verdes Reservoir
Buchanan Dam	Paradise - Magalia Dam
Camanche Reservoir - Camanche Dam	Pomona - Puddingstone Dam
Carbon Canyon Dam	Prado Dam
Del Valle Dam	Redlands; Seven Oaks Dam
Fairmont Reservoir - Fairmont Dam R. Abut	Riverside - Mathews Dam, Dike 1
Hayfork - Ruth Lake Dam [Mathews Dam]	Riverside - Mathews Dam, Main Dam
Hidden Dam	San Antonio Dam
Indian Creek Dam - Crest	San Miguel - San Antonio Dam
Lake Crowley - Long Valley Dam	Santa Fe Dam
Lake Edison - Vermilion Dam	Sierra Madre - Cogswell Dam
Lake Isabella Dam	Terminus Dam
Lake Mathews Dam	Thousand Oaks - Wood Ranch Dam & Dike
Lake Piru - Santa Felicia Dam	Warm Springs Dam
Lake Success Dam	Whittier Narrows Dam

An Illustrative Case Study on Seven Oaks Dam

Within the confines of this study, Seven Oaks Dam is selected as an illustrative example to assess the H/V spectral ratios and subsequently estimate the resonance frequency (f_0) and amplification factors. This methodology will later be applied to a larger dataset and will be used with near real-time generated shake maps, to predict locations of expected high-motion amplification and provide an immediate assessment of likely damage to the dam.

Background Information on Seven Oaks Dam

Seven Oaks Dam is a flood control dam constructed by the U.S. Army Corps of Engineers, Los Angeles District. The dam is located on the Santa Ana River in Redlands, San Bernardino County, California (34.1105N, 117.0985W). The dam has a structural height of 640 feet, and a crest length of 2,760 feet earth-rockfill dam (Mejia and Dawson, 2008). Figure 4 presents the plan view of Seven Oaks Dam along with the location of the accelerographs as given by Mejia and Dawson (2008). There are 6 three-component accelerographs of the ground motions (2 horizontal and 1 vertical) on Seven Oaks Dam. These accelerographs are located on the right abutment, right crest, center crest (surface and downhole at -152 ft), intake structure, gate chamber, and downstream (surface and downhole at -53 ft).

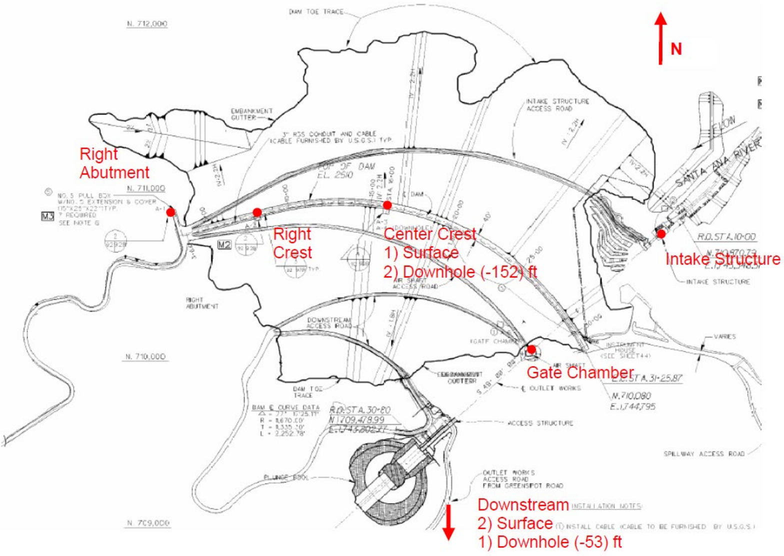


Figure 4. Plan view of Seven Oaks Dam along with the location of the accelerographs (Mejia and Dawson, 2008).

Figure 5 presents the site conditions and the location of the accelerographs located at the surface and at 53 ft at the downstream site as given by Mejia and Dawson (2008). The site consists of alluvium in the upper 37 ft underlaid by weathered bedrock which has a shear wave velocity of 3000 ft/s. The downstream site of Seven Oaks Dam represents free field conditions, and 15 digitally available records enable a more accurate estimation of the resonance frequency of the site hence the calculation of HVSR will be illustrated for the downstream site.

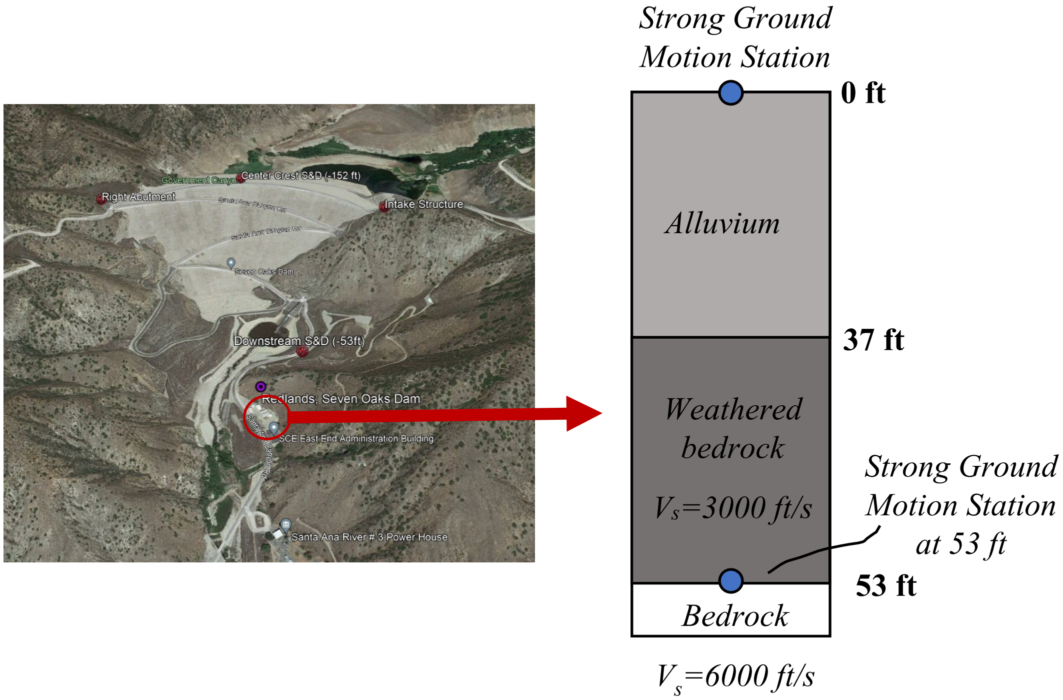


Figure 5. Site conditions at the downstream site (after Mejia and Dawson, 2008)

Ground Motion Recordings

Seismographs at Seven Oaks Dam downstream site recorded 17 earthquakes which are reported in the CSMIP network. These events are listed in Table 2.

Table 2. List of the events recorded at the Seven Oaks Dam site.

EQ#	Earthquake Name	Time USGS	M_w USGS	Epi_{dst} (km)
1	Hector Mine Earthquake	1999-10-16 09:46:44 (UTC)	7.1	93.1
2	Anza Earthquake	2001-10-31 07:56:16 (UTC)	5	86.9
3	Big Bear-02	2001-02-10 21:05:05 (UTC)	4.7	-
4	Big Bear City Earthquake	2003-02-22 12:19:10 (UTC)	5	31.5
7	San Bernardino Earthquake	2009-01-09 03:49:46 (UTC)	4.5	19
9	Ridgecrest Earthquake	2019-07-04 17:33:49 (UTC)	6.5	180.8
10	Searles Valley Earthquake	2019-07-05 11:07:53 (UTC)	5.4	188.1
11	Searles Valley Earthquake	2019-07-06 03:16:32 (UTC)	5	183.9
12	Searles Valley Earthquake	2019-07-06 03:23:50 (UTC)	4.8	193.1
13	Ridgecrest Earthquake	2019-07-06 04:13:07 (UTC)	4.8	170.2
14	Little Lake Earthquake	2019-07-06 04:18:55 (UTC)	5.4	206.7
15	Little Lake Earthquake	2019-07-06 04:19:54 (UTC)	3.8	205.1
16	Searles Valley Earthquake	2019-07-06 08:32:57 (UTC)	4.6	173.2
17	Little Lake Earthquake	2019-08-22 20:49:50 (UTC)	4.9	207
18	Barstow Earthquake	2020-01-25 03:03:34 (UTC)	4.6	110.1
19	Anza Earthquake	2020-04-04 01:53:18 (UTC)	4.9	88
20	Searles Valley Earthquake	2020-06-04 01:32:11 (UTC)	5.5	169.6

Most earthquakes are moderate events with a moment magnitude range of 4.0-7.1 with an epicentral distance of 19 to 207 km. The epicenter of the events along with the Seven Oaks Dam location is shown in Figure 6.

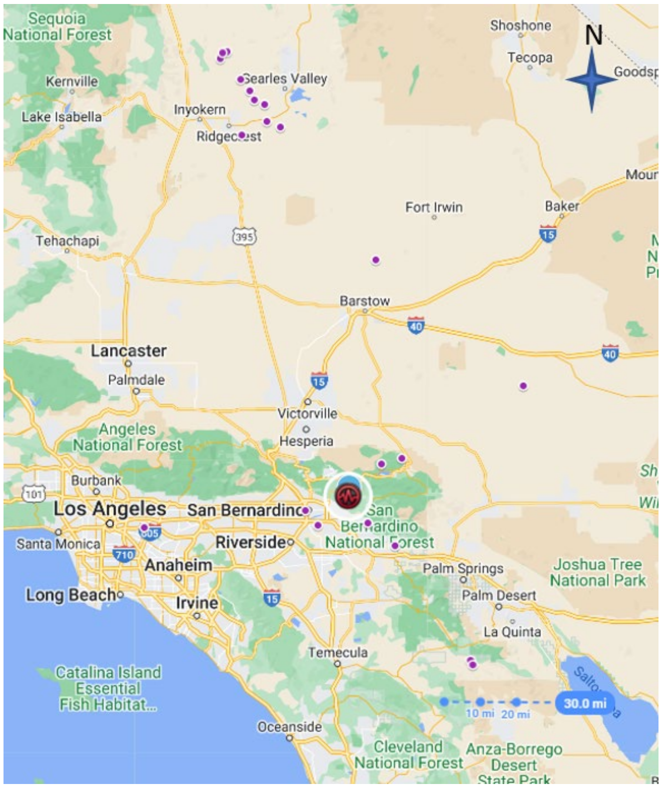


Figure 6. Epicenters of the earthquakes recorded at Seven Oaks Dam along with the location of the dam.

Among those recorded events, only a limited number of data is available at the crest on the other hand a large number of data is available at the downstream site. Considering the uncertainties involved in H/V ratio analyses to determine the resonance frequency of sites, it is more convenient to assess the downstream site since a large number of data can be used in the subsequent analysis. CSMIP network provided filtered, and baseline-corrected strong ground motion data, and most of these recorded are band-passed filtered by using Butterworth filtering to frequency levels of 0.3-33 Hz. Those motions are used directly in the analysis to assess the H/V ratio. For a limited number of strong ground motion data, only the raw recordings were available, and these are filtered by using Seismo Signal 2022 software. Table 3 presents a summary of the recorded ground motions the at Seven Oaks Dam site and the maximum ground acceleration for 3 components. The maximum peak ground acceleration (geometric mean of the two-horizontal components) of the recorded ground motions at downstream sites varies between 0.0007 to 0.0626 g.

Table 3. List of the events and corresponding maximum ground acceleration values recorded at Seven Oaks Dam.

Location of the Accelerograph		a_{max} (g)																				
	EQ#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Project Office	**360°**	0.0505						0.1545														
	90°	0.0631						0.1171														
	UP	0.0286						0.0006		0.0704												
Center crest surface	**360°**							0.1544														
	90°							0.1171														
	UP							0.0507														
Center crest downhole	**360°**							NA														
	90°							0.0270														
	UP							0.0322														
Right crest	**360°**																					
	90°																					
	UP																					
Right abutment	**360°**			0.0047	0.0130			0.0588														
	90°			0.0071	0.0113			0.0344														
	UP			0.0042	0.0082			0.0230														
Tunnel chamber	**360°**							0.0164														
	90°							0.0096														
	UP							0.0078														
Downstream surface	**360°**		0.0120	0.0417	0.0407			0.0557		0.0089	0.0011	0.0006	0.0006	0.0011	0.0019	0.0019	0.0010	0.0012	0.0024	0.0063	0.0037	
	90°		0.0081	0.0608	0.0313			0.0704		0.0085	0.0012	0.0008	0.0010	0.0009	0.0022	0.0022	0.0013	0.0012	0.0026	0.0067	0.0043	
	UP		0.0055	0.0173	0.0115			0.0211		0.0039	0.0005	0.0003	0.0004	0.0004	0.0013	0.0013	0.0005	0.0005	0.0009	0.0027	0.0017	
Downstream downhole	**360°**							0.0291														
	90°							0.0236														
	UP							0.0080														

Calculation of H/V (or HVSR) curves

The method to estimate the H/V (or HVSR) was proposed by Nakamura (1989) to interpret microtremor measurements. As mentioned before, the method is also applied to strong ground motion recordings (e.g., Lermo & Chavez-Garcia 1993, etc.) to implement the H/V procedure to identify the fundamental resonance frequency of sedimentary deposits.

The availability of free software “Geopsy” (Wathelet et al, 2020) enables a practical assessment of H/V ratios which is used in this study. Figure 7 presents the 3-component acceleration time histories recorded at the downstream site which are used to estimate the H/V ratios at the site and the processing of these recordings is achieved using “SeismoSignal” 2022 software. Following the procedure described above, for each earthquake recording, a different time window is selected to capture the intense part of the S-waves in the ground motion and this window is cosine tapered (5%) and Fourier transformed by using Geopsy software. The Fourier Amplitude spectra (FAS) are smoothed with the Konno and Ohmachi (1998) algorithm with a b-value of 40 using a logarithmic equation. The geometric mean of the horizontal components is calculated and divided by the vertical component.

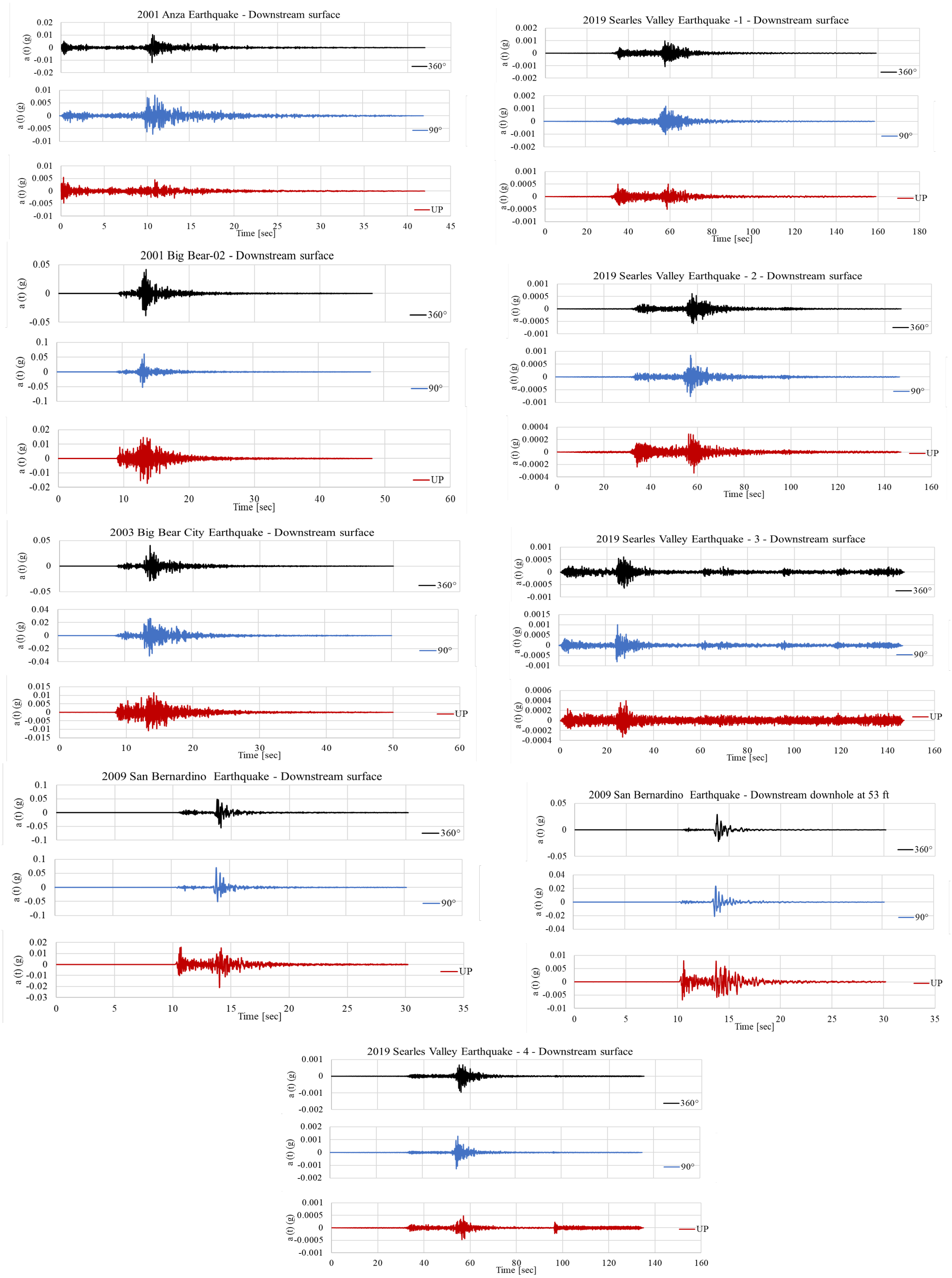
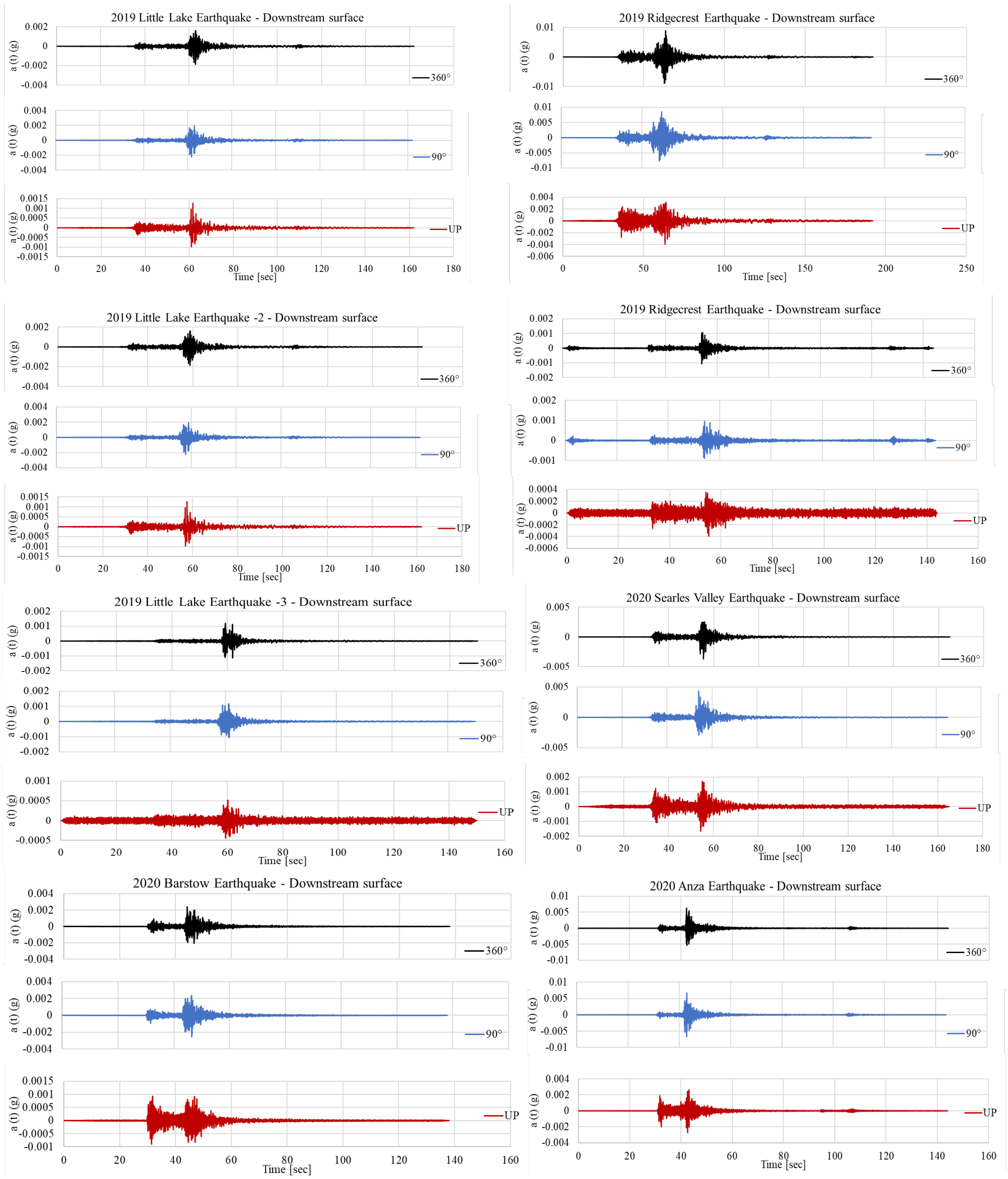


Figure 7. Acceleration time histories recorded downstream site


2019 Little Lake Earthquake - Downstream surface

2019 Ridgecrest Earthquake - Downstream surface

2019 Little Lake Earthquake -2 - Downstream surface

2019 Ridgecrest Earthquake - Downstream surface

2019 Little Lake Earthquake -3 - Downstream surface

2020 Searles Valley Earthquake - Downstream surface

2020 Barstow Earthquake - Downstream surface

2020 Anza Earthquake - Downstream surface

Figure 7. Acceleration time histories recorded downstream site (cont'd)

The results obtained are presented in Figure 8. Site effects as can be inferred from this figure indicates a resonance frequency between 6.1 and 7.5 Hz at the downstream site. The results show a consistent agreement of estimates for the HVSR, and the resonance frequency is estimated as 6.88 Hz (predominant period 0.145 sec) which is reasonable considering the stiff nature of the deposit with high shear wave velocity profile at the downstream site. The solid red line shows the average of the H/V curves obtained using 15 earthquake recordings. However, the results suggest that considerable uncertainties are associated when the amplification factors are investigated. These uncertainties are related to the assumptions involved in HVSR analysis. The main assumption of this analysis is that the horizontal and vertical ground motions at the firm bedrock are identical and only the horizontal motions, not the vertical component, are amplified significantly by site conditions. Hence it should be carefully assessed if the HVSR bedrock is constant as discussed by Rong et al. (2017). This study also discussed that the vertical site response has a significant effect on the calculated HVSR curves. A careful examination should also be made for selecting the window length for the arrival of S-waves which contributes to uncertainties. All these aspects will be further studied in future studies.

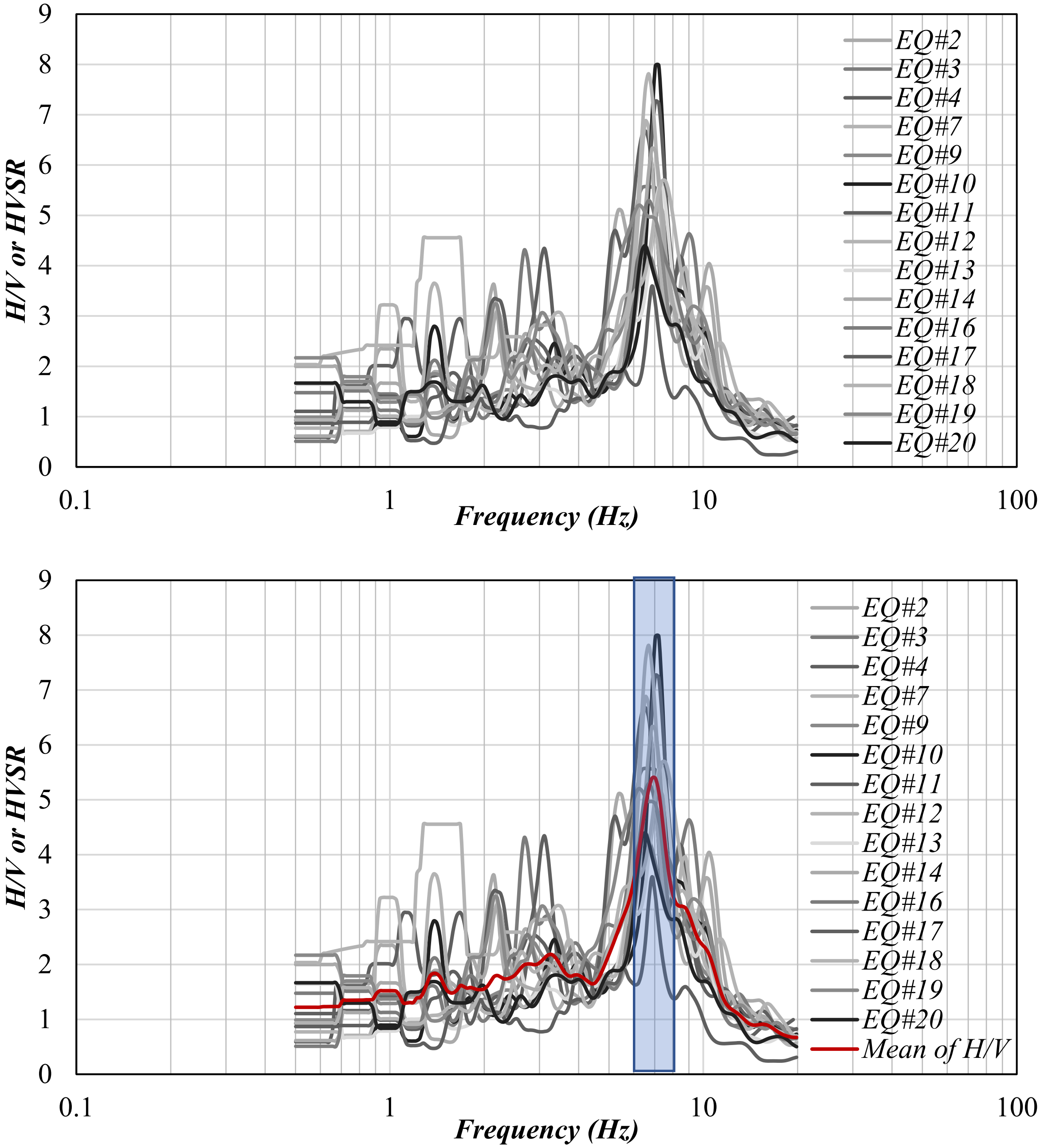


Figure 8. H/V ratios at the downstream site at Seven Oaks Dam for different events along with the average curve.

Table 4 presents the resonance frequency (f_0) and amplification factor (A_0) results for each earthquake recording at the downstream site along with moment magnitude (M_w), epicentral distance ($Epi_{dist.}$), and maximum ground acceleration (a_{max}). The effect of distance and depth of vibration source on the H/V ratios will be studied in future studies.

Table 4. Summary of the results for Seven Oaks Dam downstream site

EQ#	Earthquake Name	M_w USGS	Epi_{dst} (km)	a_{max} (g)			f_o	A_o
				360°	90°	UP		
2	Anza Earthquake	5	86.9	0.0115	0.0078	0.0059	6.14	3.82
3	Big Bear-02	4.7	-	0.0420	0.0607	0.0178	6.69	5.56
4	Big Bear City Earthquake	5	31.5	0.0419	0.0309	0.0125	6.70	6.59
7	San Bernardino Earthquake	4.5	19	0.0577	0.0705	0.0215	6.61	6.80
9	Ridgecrest Earthquake	6.5	180.8	0.0089	0.0085	0.0039	6.69	4.28
10	Searles Valley Earthquake	5.4	188.1	0.0011	0.0012	0.0005	7.43	6.65
11	Searles Valley Earthquake	5	183.9	0.0006	0.0008	0.0003	7.32	6.79
12	Searles Valley Earthquake	4.8	193.1	0.0006	0.0010	0.0004	6.66	7.75
13	Ridgecrest Earthquake	4.8	170.2	0.0011	0.0009	0.0004	6.92	4.78
14	Little Lake Earthquake	5.4	206.7	0.0019	0.0022	0.0013	7.08	6.14
16	Searles Valley Earthquake	4.6	173.2	0.0010	0.0013	0.0005	6.99	4.99
17	Little Lake Earthquake	4.9	207	0.0012	0.0012	0.0005	7.12	4.36
18	Barstow Earthquake	4.6	110.1	0.0024	0.0026	0.0009	7.48	5.68
19	Anza Earthquake	4.9	88	0.0063	0.0067	0.0027	6.57	5.03
20	Searles Valley Earthquake	5.5	169.6	0.0037	0.0043	0.0017	6.78	4.09

Site Response Analysis

1-D seismic site response analysis is performed using the software Deepsoil by Hashash et al. (2020) with an equivalent linear frequency domain method for the downstream site at Seven Oaks Dam. Site conditions at the downstream site are provided by Mejia and Dawson (2008) which are previously presented in Figure 5. A V_s profile for the downstream site is not fully available which restricts an accurate 1-D site response analysis, especially for the relatively soft layer of alluvium deposit, leading to larger uncertainty. A set of sensitivity analyses are performed to predict the surface recording by using the downhole recording at 53 ft as an input motion to compensate lack of V_s information. The results present an overall understanding of the site conditions however additional information is required for a more precise estimation of the amplification factors and site resonance frequency. Figure 9 presents the V_s profile used in the analysis of the downstream site.

In order to define the shear modulus degradation and damping characteristics of the site Rollins et al. (2020) study is used for the alluvium site which consists of gravelly materials and Idriss (1999) for the weathered rock. Figure 10 presents Fourier Amplitude Ratio determined for the downstream site by 1-D site response analysis along with the results obtained from HVSR analysis. The site response analysis was performed by using the 2009 San Bernardino Earthquake which is the only recording available at the downstream surface and downhole whose PGA is calculated as 0.0577 g, 0.0705 g, and 0.0215g for 360°, 90°, and vertical components respectively. The lack of adequate knowledge of the upper alluvium layer may potentially cause unrealistic amplification factors. When the HVSR curves are compared with the theoretical amplification spectra obtained from site response analysis in Figure 10, it is observed that the resonance frequencies are mostly close (e.g., 5.3 Hz and 6.4 Hz) however the amplitudes are dramatically different. Further data is needed to compare the result of both methods which may be performed with a more accurate V_s profile and using several different ground motion recordings.

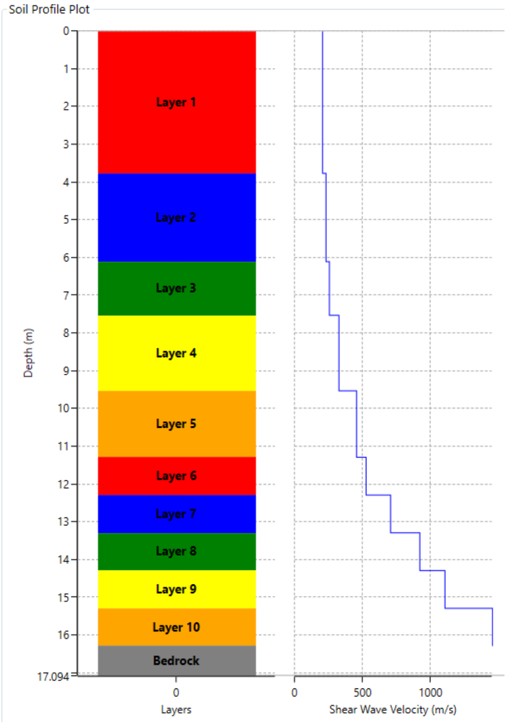


Figure 9. Estimated V_s profile of the downstream site at Seven Oaks Dam.

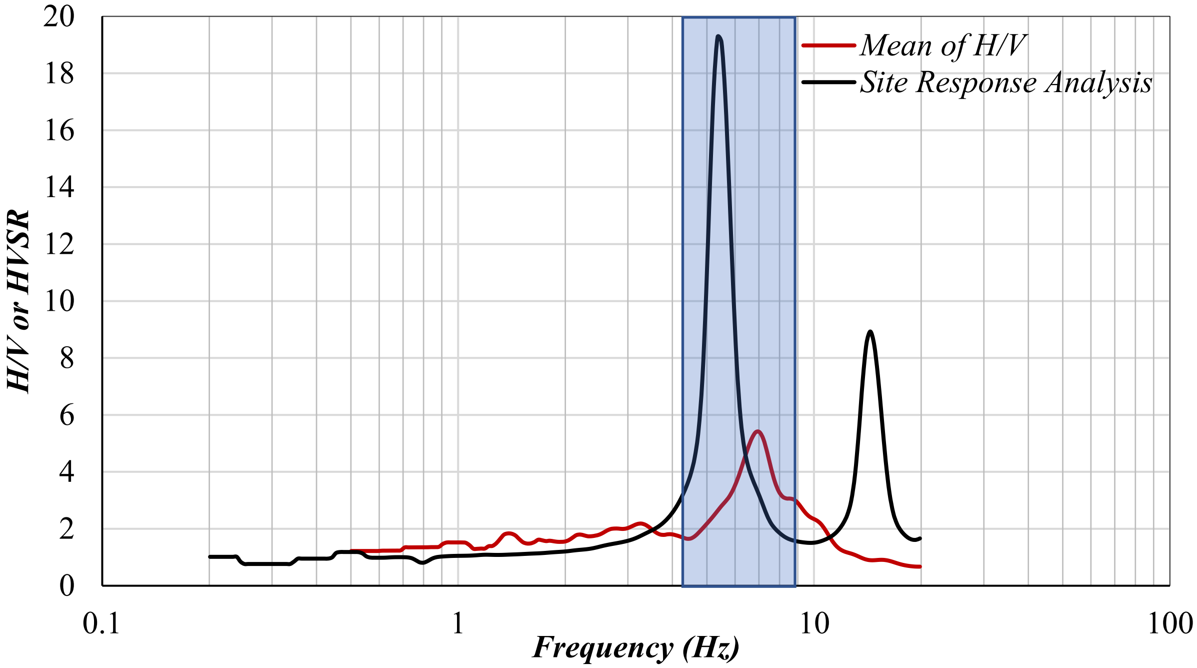


Figure 10. Comparison of HVSR and 1-D site response analysis results for the downstream site at Seven Oaks Dam.

Calculation of G_{max} and Damping

Seismic recordings of vertical array of accelerometers in the downstream site is used for extracting shear stress-strain loops to determine the corresponding value of maximum shear modulus, G_{max}. Following the procedure by Abdel-Ghaffar and Scott (1979a, b), Lin and Chao (1990), Koga and Matsuo (1990), and Lin (1994) and adopted by Zeghal and Elgamal (1994), shear strain versus shear stress loops are investigated at the downstream site by using the 2009 San Bernardino Earthquake recordings which is the only recording available at the downstream surface and downhole at 53 ft. Average shear stress-strain values are determined with the following formulations given in Equations 1 and 2 by Zeghal and Elgamal (1994).

$$\tau_z = \frac{1}{2}\rho z\left(a_2 + \left(a_2 + (a_1 - a_2)\left(\frac{z}{h}\right)\right)\right) \qquad \text{Eq. (1)}$$

$$\gamma = (d_1 - d_2)/h \qquad \text{Eq. (2)}$$

where τ_z = average shear stress, ρ = density of the soil layer, a_2=horizontal acceleration at the surface, a_1=horizontal acceleration at depth z, $d_1 and\ d_2$ =displacement at the surface and downhole and h=the layer thickness.

The strong ground motion data obtained from the 2009 San Bernardino Earthquake is pass-filtered and the analysis is performed for the 90° component which is the dominant direction. Figure 11 shows the acceleration time history for the 90° component of the 2009 San Bernardino Earthquake. As can be inferred from this figure, ground acceleration has a low amplitude between 10.4-13.6 sec. Figure 12a presents the shear strain versus shear stress graph for the 2009 San Bernardino Earthquake for the entire motion and Figure 12 b presents the stress-strain curve for the 11.0-11.2 sec cycle which is used to determine the G_{max} value at the downstream site considering the small shear strain levels at that time window. This G_{max} value represents an average estimate of the alluvium layer and weathered rock. G_{max} can also be estimated directly based on V_s value with the expression of $G_{max}=\rho \cdot V_s^2$. Based on assumed V_s value for alluvium, the method of extracting G_{max} based on strong ground motion values results in reasonable estimates.

Small strain equivalent linear (secant) shear modulus is estimated from shear stress-strain loops. The results cannot be evaluated as the shear wave velocity profile is not available for the downstream sites. But considering that an estimated V_s profile was used in site response analysis the results are reasonable which should be further investigated with more information.

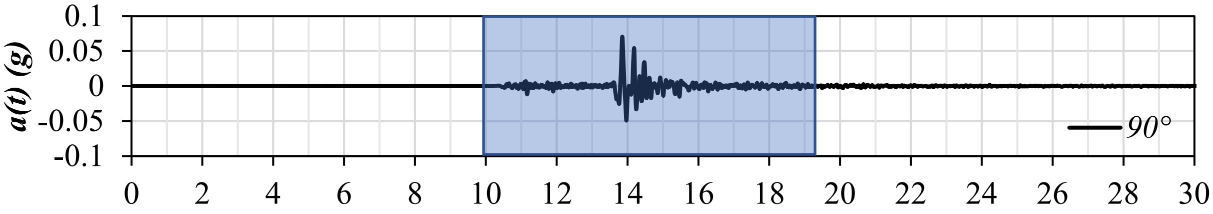


Figure 11. Acceleration time histories of 2009 San Bernardino Earthquake at downstream site surface

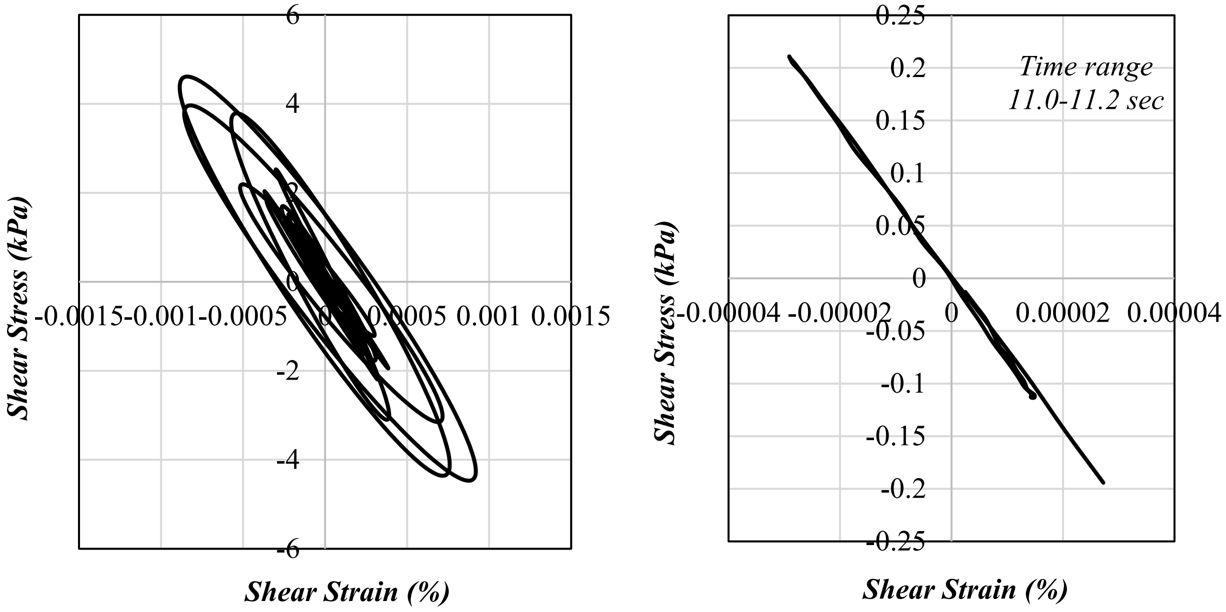


Figure 12. Shear strain versus shear stress graph for the 2009 San Bernardino Earthquake a) for the entire motion and b) for 11-11.2 sec cycle.

Conclusions

The purpose of this paper is to improve our understanding of the seismic response of earth dams and create a framework for strong-motion data processing that can lead to improvement in the seismic design code provisions and practices with respect to earth dams. For this purpose, CSMIP earthquake recordings from different locations on the dams (toe, crest, abutment, etc.) are assessed to develop Horizontal to Vertical (H/V) spectral ratios for selected dam locations estimated directly from the recorded motions to assess the fundamental resonance frequency of the sites and amplification factors. For this purpose, the results of Seven Oaks Dam are presented as an illustrative example. 15 earthquakes were recorded by Seven Oaks downstream site. These recordings were assessed by using Geopsy software and for each recording H/V ratios are calculated following the procedure offered by Nakamura (1989). The average of the H/V ratios are also determined which indicates the predominant frequency for the downstream site as 6.88 Hz. Amplification factors for each strong motion station are obtained from the H/V curve which has large uncertainties. 1-D site response analyses are performed; however, the lack of an accurate V_s profile enables an accurate comparison of the available models. Further research is needed to verify the applicability of the current method to assess the amplification factors. Following the procedure by Abdel-Ghaffar and Scott (1979a, b), Lin and Chao (1990), Koga and Matsuo (1990), and Lin (1994) and adopted by Zeghal and Elgamal (1994), shear strain versus shear stress loops are investigated at the downstream site by using the 2009 San Bernardino Earthquake recordings and results found reasonable for a stiff site as the downstream of Seven Oaks Dam. However, this suggests that this case history does not fully satisfy the minimum requirements of the methods discussed in this study, and further site investigation data and digital recording at the vertical arrays at the crest surface and downstream sites are required to assess dynamic properties.

Acknowledgments

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