THE USE OF 3D MODELING FOR THE PREDICTION OF THE SEISMIC DEMANDS ON THE GRAVITY DAMS

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Abstract

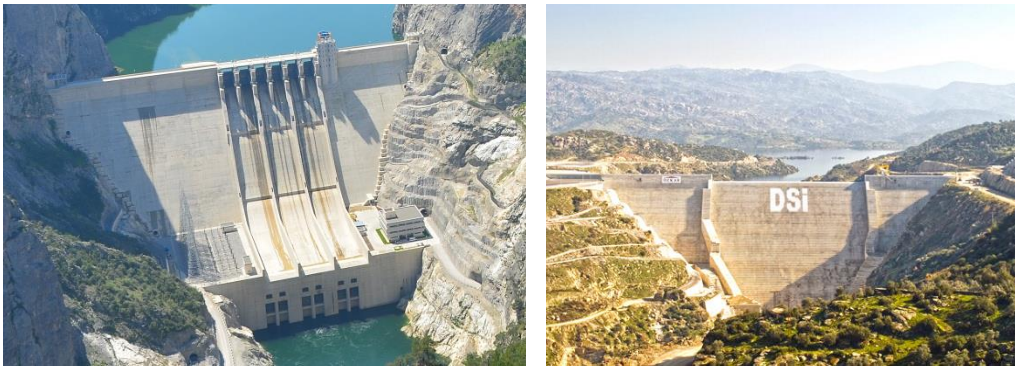
Seismic behavior of gravity dams has long been evaluated using a representative 2D monolith for the system. Formulated for the gravity dams built in wide-canyons, the assumption is nevertheless utilized extensively for almost all concrete dams due to the established procedures as well as the expected computational costs of a three dimensional model. However, a significant number of RCC dams, characterized as such systems, do not conform to the basic assumptions of these methods by violating the conditions on canyon dimensions and joint-spacing/ details. Based on the premise that the 2D modeling assumption is overstretched for practical purposes in a variety of settings, the purpose of this study is to critically evaluate the use of 2D modeling for the prediction of the seismic demands on these systems. Using a robust SSI approach, the difference between the 2 and 3D response for gravity dams are investigated first in the frequency domain. Rigorous frequency domain solutions for both cases were used in order to compare the frequency response functions for the crest response quantities. In the 3D configuration, monolithic models with no construction joints as well as models composed of independent monoliths were used as the two ideal cases in order to investigate the behavior of the 3D model. The effect of the narrowness of the canyon as well as the foundation rigidity was evaluated for a range of canyon widths and foundation moduli and the differences between the natural frequencies and the damping ratios between the two modeling approaches were presented. As the engineering decision parameters on such systems are based on time domain parameters such as the stresses and displacements, next, a time domain comparison between the responses of 2 and 3D models were obtained using 70 different ground motions. The maximum crest displacement and toe stress values for the 2 and 3D models were compared for different canyon widths and foundation moduli. The scatter of the differences between the 2 and 3D model results were presented for different ground motions in order to show the possible bias introduced into the analysis results due to the modeling approach. The results of the study show that even for relatively wide canyons, the 2D analysis can lead to misleading predictions.

Keywords: RCC Dam, seismic design; soil-structure interaction; 2D vs. 3D analyses; frequency domain

1. Introduction

The analyses of concrete gravity dams are customarily conducted in a 2D configuration due to the computational costs of the detailed simulation in a 3D setting. Although the limitations of the 2D analyses are not well described, 2D analyses are still considered to be the basis of dam design and evaluation. One possible reason for the popularity of the 2D analyses may be the development of the soil-structure-reservoir interaction based on these conditions. Intensive research has been conducted in the past four decades on the seismic analysis and design of concrete gravity dams, notably by Chopra and his colleagues, developing a comprehensive approach to the dam-reservoir-foundation incrementally from the simpler 2D setting to the full 3D setting for arch dams [1-8]. In spite of the development of the 3D procedures, regarded as the domain for arch dams, the provisions for the seismic design and evaluation of gravity dams [9,10] are mostly based on 2D model considerations.

2D analyses are extensively used for the design of gravity dams (almost regardless of the geometry of the problem) assuming the following conditions are valid, i.e. 1) A plane stress condition permitted by the use of traditional intermittent expansion joints separating monoliths or 2) A plane strain condition for a system constructed in a wide canyon. With the extensive use of the RCC material, both of these assumptions are questionable due to the construction technique. Construction joints are hardly built in the former fashion. Joints are prepared usually by rotary saws in RCC dams, partial slicing at the upstream or downstream facades or often alternating the cutting at different lift joint levels in order to expedite the construction. The joint spacing is also considerably larger in new dams owing to the low heat of hydration of RCC. With the speed advantage provided by RCC construction, gravity dams are also being built in narrow valley locations otherwise suitable for arch dams such as the examples shown in Fig. 1.



(a) Boyabat Dam (b) Cine Dam

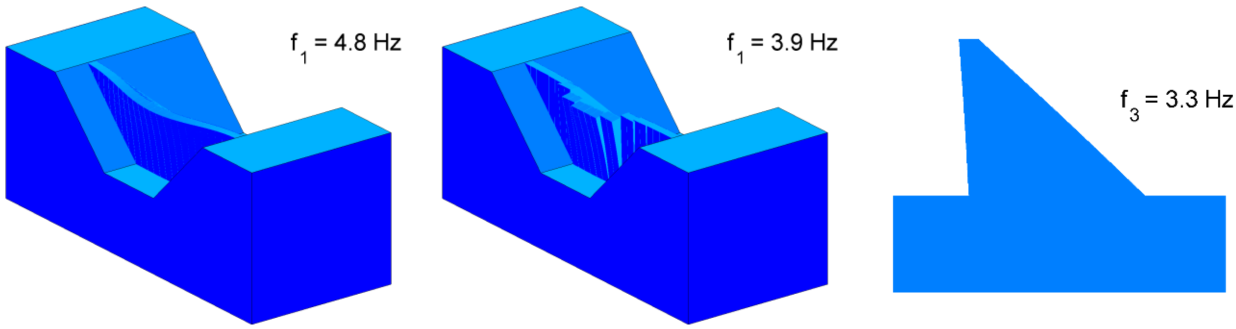
Fig. 1 – RCC dams in narrow valleys

In the context of the discussion above, the main purpose of this study is to investigate the representative value of the 2D modeling approach in lieu of the 3D analyses for the seismic assessment of the gravity dams, specifically for the RCC systems. For this purpose, the frequency response functions of a range of generic dam systems were obtained and compared for the 2 and 3D settings. Rigorous frequency domain solutions for both cases were used in order to compare the frequency response functions for the crest response quantities. In the 3D configuration, monolithic models with no construction joints as well as models composed of independent monoliths were used as the two ideal cases in order to investigate the behavior of the 3D model. The corresponding cases in the 2D configuration were chosen as the plane strain and plane stress solutions, respectively. The effect of the narrowness of the canyon on the frequency response functions were evaluated by assuming the generic system to be built in a canyon with the width varying between two to twelve times the dam height. The first mode frequency and the damping ratio were estimated for these systems and the differences between the 2 and 3D solutions were presented. Given the need for the comparison of engineering response parameters in the time domain as well as the frequency domain, a set of 70 ground motions were then used to compare the peak time history response values for the displacements and the stresses between the 2 and 3D models.

The study is subject to some limitations. Given the primary purpose of comparing the 2/3D behavior, the ground motion effect was only assumed to be in the direction perpendicular to the dam axis: multidirectional effect was not considered. In case of independent monoliths, the contact forces and the possible pounding between the monoliths in the cross-stream direction were not considered. Finally, the spatial asynchronous nature of the ground motion was also not included within the scope of the analyses.

2. Numerical Modeling of the Seismic Response of Gravity Dams

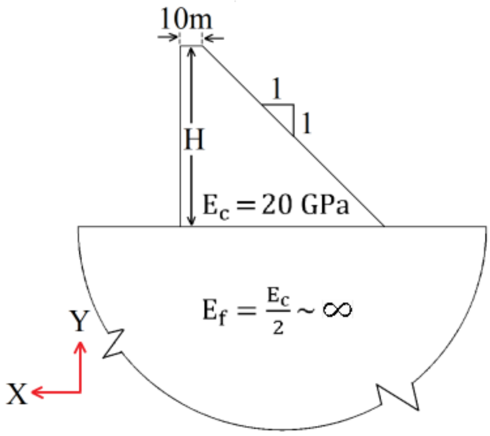
Two different model idealizations were used in order to represent the 3D behavior of dam systems (Fig. 2) as shown by the first Eigen modes for a system with identical dam and foundation moduli of 20 GPa. The first idealization, Fig. 2a, was fully monolithic, representing the RCC dams built with interlocking expansion joints and/or partial expansion joints. The second, named as the "independent" case from hereon (Fig. 2b), represented the typical gravity dam construction, (applicable to some RCC dams with fully sawed expansion joints), with independent monoliths only to be connected at the foundation level. In this case, it was assumed that the construction joints in the system were large enough to preclude an interaction between the neighboring monoliths in both the cross-stream and stream directions. 20 node brick elements and 15 node wedge elements were used to model the dam body in these 3D settings. In two dimensions, the plane stress and the plane strain model idealizations were used to represent the independent and monolithic cases, respectively. Quadratic elements were used in the 2D models. The first mode shape for a 2D model with identical properties is presented in Fig. 2c.



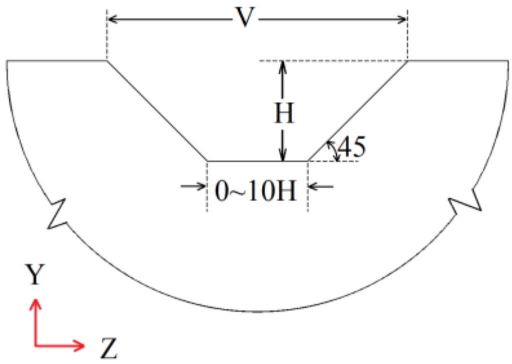
(a) Monolithic system (b) System with independent monoliths (c) 2D system

Fig. 2 – Eigen modes, monolithic idealization, system w/independent monoliths and the 2D model

For the sake of simplicity, all the systems considered within the study were assumed to be of a generic 3D geometry built in canyons with 45 degree sloping shoulders as shown in Fig. 3, treating the width of the valley and the foundation modulus as the variables effective in determining the response of the system. The upstream face of the dam was assumed flat while the downstream was modeled with a slope of 1V/1H. The reservoir was assumed to be at full capacity. In order to investigate the effect of canyon width on the 3D response of a given system, this gravity dam section (with a Young's modulus of 20 GPa) was assumed to be built in five different canyon settings. The width of the canyon (V) was chosen as 180m, 240m, 320m, 480m and 960m (designated as 2H, 3H, 4H, 6H and 12H in terms of the dam height, respectively). The frequency response was evaluated at four different moduli ratios for the foundation. The foundation was first treated as rigid, then assigned Young's Moduli (E_f) of 40, 20 and 10 GPa in order to obtain E_f/E_c ratios of ∞, 2, 1 and 0.5, respectively. The hysteretic damping constant for the foundation was assumed as 0.1 while the damping ratio for the dam body was assumed as 5%. The base excitation was assumed in the direction of the stream; the response of the dam was only evaluated in this direction as well (perpendicular to the axis of the dam). Semi-infinite 1D channel idealization was used for the reservoir with a bottom absorption coefficient of 0.9.



(a) Dam cross-section



(b) Canyon geometry

Fig. 3 – The generic 3D dam and canyon setting

In order to compare the behavior of 3D models to the 2D counterparts, a simple analysis methodology to obtain frequency domain functions was utilized herein. Given the full frequency response matrix is hard to present, the frequency response function for the crest acceleration at the center of the dam system was used as a representative tool. The frequency response functions for the systems were obtained by applying a pulse with a very short duration as the base excitation of the system. The frequency response functions for 2 and 3D systems are compared first. Given the solutions to engineering problems are usually based on the time domain quantities, such as the stresses and the displacements, the time domain effects of the differences between the FRFs of the 2 and 3D models are then investigated.

3. The Seismic Response of Gravity Dams in 2/3D Settings

The frequency response functions for the 3D models at different canyon widths and foundation moduli are compared to their 2D counterparts in Fig. 4 and Fig. 5 for the crest displacement at the center of the dam. The natural frequencies and damping ratios for the 2D model, obtained using the half-power bandwidth method, are presented in Table 1. The natural frequencies of the plane-strain 2D and the 3D models for the monolithic systems were obtained significantly different with the two results converging with increased canyon width as expected. There also appeared to be a significant difference between the resonant amplitudes of the models. The trend was not very different for the systems comprised of independent monoliths. In contrast to the expectations, the large differences between the 2D plane-stress model and the 3D models are also evident for a wide range of scenarios (of canyon width and moduli ratios, Fig. 5).

Table 1 – Fundamental frequency and damping ratios for the fundamental mode of 2D models

Material	**Plane Strain**		**Plane Stress**	
E_f/E_c	**f_1 (Hz)**	**ξ_1(%)**	**f_1 (Hz)**	**ξ_1(%)**
0.5	2.3	28.4	2.4	27.3
1.0	2.9	19.7	3.0	18.7
2.0	3.4	12.8	3.4	12.3
∞	4.1	4.3	4.1	4.3

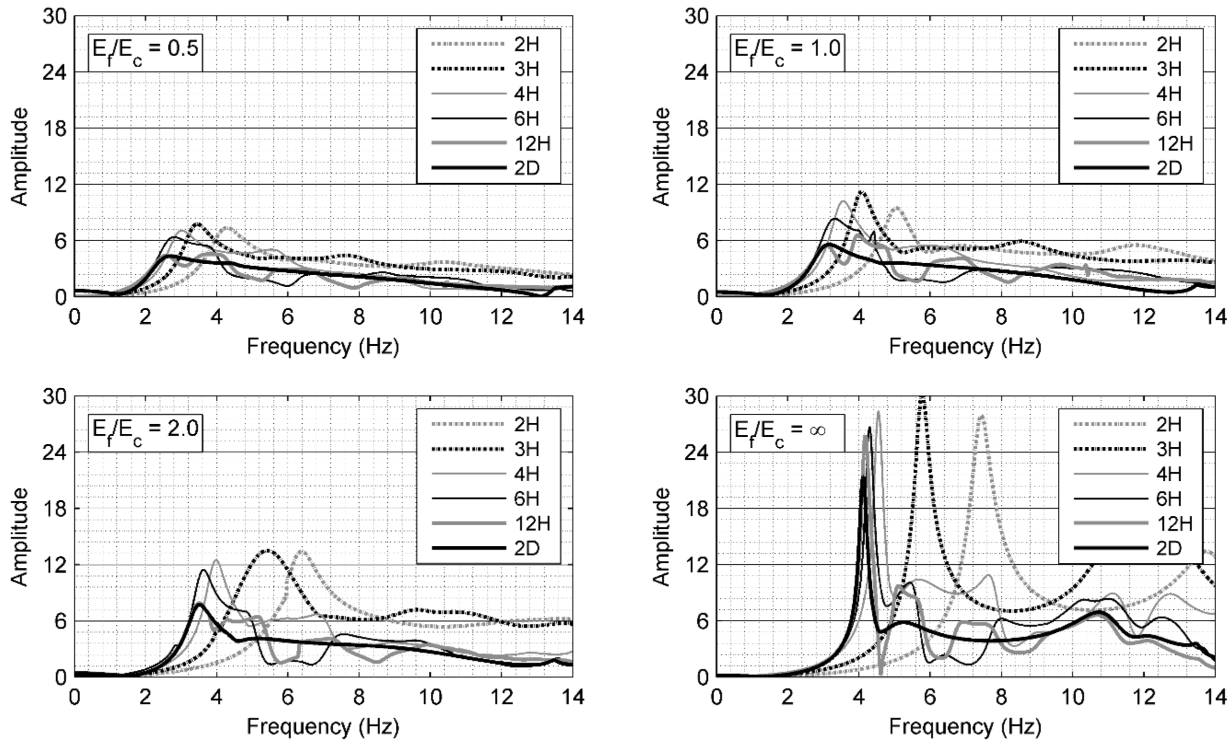


Fig. 4 Frequency response functions, monolithic models vs. plane strain models

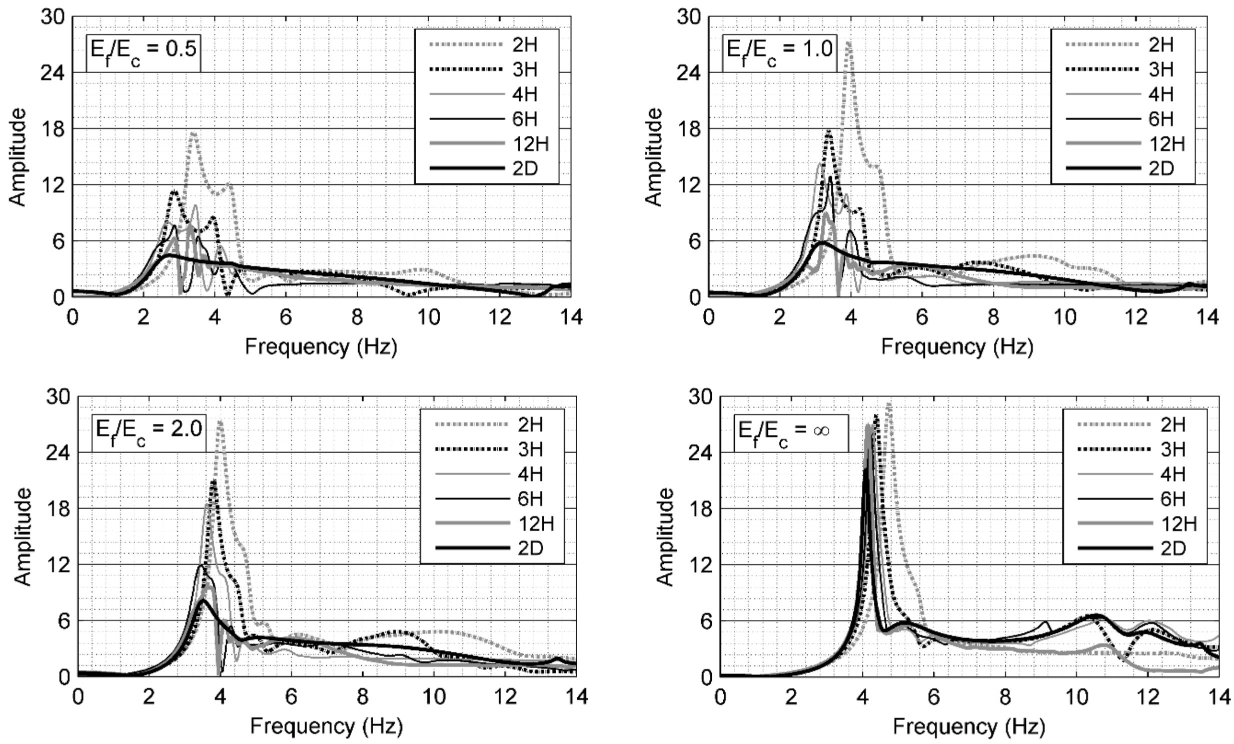


Fig. 5 Frequency response functions, independent monolith idealization vs. plane stress models

The differences in the natural frequencies and damping ratios for the 2 and 3D idealizations of the same system are presented in Table 2. For the monolithic idealization of the dam, there are significant differences in the fundamental frequencies of the 2 and 3D models for the narrow canyons. The fundamental frequency of the 3D rigorous solution agreed well with the 2D prediction at the 12H canyon width, however, the difference was greater than 10% for canyon widths less than 6H. The difference in the fundamental frequency between the 2 and 3D models was amplified by the decrease in the ratio of the foundation/structure moduli: i.e. softer foundation medium caused 3D models to yield higher fundamental frequency values compared to 2D models. For the idealization with the independent monoliths, the difference between the fundamental frequency of the 2D and the 3D models decreased to some extent. For systems in narrow canyons, the difference in the fundamental frequencies was still significant. At the E_f/E_c ratio of 0.5, the natural frequency of a 3D model with independent monoliths in a canyon 2H wide was 29% higher than a 2D counterpart, showing the significant coupling between the monoliths due to the foundation. In conclusion, even with the assumption of perfectly separated monoliths, the coupling between the monoliths due to the common foundation boundary condition was significant. The difference in the fundamental frequency between the 2 and 3D modeling approaches was still large provided that the dam was built on a flexible foundation.

Table 2 – Fundamental frequency and damping ratios for 3D systems with corresponding differences to 2D models

Material E_f/E_c	Width	Monolithic				Independent Monoliths			
		f_1 (Hz)	Δf_1 (%)	ξ_1 (%)	$\Delta\xi_1$ (%)	f_1 (Hz)	Δf_1 (%)	ξ_1 (%)	$\Delta\xi_1$ (%)
0.5	2H	4.1	-44.0	14.0	102.3	3.4	-28.6	8.9	206.4
	3H	3.4	-31.5	14.4	97.2	2.8	-14.0	11.1	145.1
	4H	2.9	-19.9	17.1	66.1	2.5	-5.5	15.7	74.0
	6H	2.5	-9.1	21.7	31.1	2.3	5.3	21.2	28.5
	12H	2.4	-3.4	30.1	-5.7	2.4	1.7	28.9	-5.4
1.0	2H	5.0	-41.8	9.9	99.0	3.9	-23.1	6.4	192.2
	3H	4.0	-27.3	10.3	92.2	3.3	-9.4	7.9	136.7
	4H	3.5	-16.4	12.4	58.5	3.1	-2.6	8.9	110.1
	6H	3.1	-6.8	16.6	19.0	2.9	4.5	14.0	33.9
	12H	3.0	-3.0	24.6	2.8	2.8	7.5	25.3	-26.1
2.0	2H	6.3	-45.8	9.3	37.6	4.4	-22.7	6.1	101.6
	3H	4.8	-29.2	9.8	30.6	3.8	-9.6	6.7	84.1
	4H	3.9	-13.0	9.6	33.8	3.6	-5.0	7.1	72.5
	6H	3.6	-4.2	10.5	21.7	3.4	1.2	10.2	20.1
	12H	3.5	-2.8	12.1	5.8	3.3	3	16.3	-24.5
∞	2H	7.5	-45.2	5.2	-17.3	5.3	-22.9	5.2	-17.3
	3H	5.8	-29.1	5.0	-14.0	4.4	-6.0	4.8	-10.4
	4H	4.5	-9.7	4.3	0.0	4.3	-5.3	4.8	-10.4
	6H	4.3	-4.4	4.3	0.0	4.3	-5.3	4.3	0.0
	12H	4.1	-1.0	4.3	0.0	4.2	-1.2	4.5	-4.4

Comparison of the 1st mode damping ratios for the 2 and 3D models shows there were significant differences in the damping ratios between the two idealizations. For a monolithic system, the damping ratio estimate for a 2D model appears to be generally significantly larger than the 3D counterpart (Table 2). The 3D solution agrees better with the 2D counterpart only for higher E_f/E_c and V/H values. The damping ratios agreed well only for V/H ratios of 12, i.e. for the case when the 2 and 3D solutions converged. For the case with the independent monoliths, much larger differences between the response peaks of the 2 and 3D solutions were observed. The highest peaks compared to the 2D results were observed especially at lower E_f/E_c ratios corresponding to large differences in the damping ratio estimates between the models. The difference reduced as the canyon width increased. The 2D models appeared to yield significantly higher damping ratios compared to their 3D counterparts. In conclusion, for the foundation modulus equal or lower than the structure modulus, 2D rigorous solution appeared to significantly flatten the response peak even for systems in very wide canyons such as those with width to height ratios of 6.

4. Time Domain Effects

The comparison of the frequency response parameters is effective only to an extent in identifying the different behavior of the chosen models. While comparing the peak response values (or the equivalent damping), the location of the frequency and the corresponding interaction with the ground motion is inadvertently ignored. The effects of both discrepancies can only be simplified to a comparative basis in the time domain results. The consideration of the response in the time domain is also essential as almost all of our engineering decision parameters are based on time domain results. Naturally, the uncertainty due to variation in the ground motions is introduced to the analysis results in order to quantify the effect of the different frequency responses on the engineering demand parameters.

A ground motion suite chosen from the Pacific Earthquake Engineering Research (PEER) strong motion database [11] was used in order to compare the response of the 2 and 3D models in the time domain. The suite, comprised of 35 pairs of time histories, was chosen so as to reflect the different characteristics of the ground motions on the chosen demand parameter. The recordings, from 18 different earthquakes in a magnitude range of 6.2 to 7.6, were selected from sites designated as rock/hard rock (NEHRP site conditions A and B) with epicentral distances of 0 to 57 km (Table 3).

The crest displacement of the dam and maximum principal stress at the upstream face (both located at the central monolith for the 3D models) were chosen as the response quantities of interest for comparison purposes. Using these demand parameters, the difference statistics between the 2 and 3D modeling approaches were obtained for the chosen ground motions which can help the designers predict the expected difference of their own 2D solution from the 3D counterparts. The relative difference between the maximum of the time history response for the 2 and 3D models are computed using Equation 1 separately for each ground motion. The crest displacement and the maximum principal stress at the base of the dam were the chosen response quantities.

$$\varepsilon_{disp}(\%) = \frac{d_{\text{top}}^{2D} - d_{\text{top}}^{3D}}{d_{\text{top}}^{3D}} \times 100 \qquad \& \qquad \varepsilon_{stress}(\%) = \frac{S_1^{2D} - S_1^{3D}}{S_1^{3D}} \times 100 \tag{1}$$

The differences between the 2 and 3D predictions for each model are presented in Fig. 6 in order to show the common range of errors one can obtain by using a 2D analysis tool for predicting the performance of this essentially 3D system. Each point for a given V/H ratio represents the % difference between the 2 and 3D models for a particular ground motion irrespective of the scale of the motion. The results for the 2D plane strain and plane stress models were compared to their counterparts, the monolithic and the independent monolith case, respectively, in the 3D setting. The mean values as well as the ± standard deviation of the difference between the 2 and 3D predictions of the crest displacement are also presented. The statistics of the particular V/H ratio were calculated considering the results for the 70 different ground motions utilized.

For the monolithic systems, the results show a large variation in the displacement predictions corresponding to the difference in the 2 and 3D frequency response functions as well as the frequency contents of the utilized motions. As given in Fig. 6, a 2D model can predict the top displacement by as much as 250% over the 3D counterpart for a narrow canyon. The error in the estimate was reduced with the increasing canyon width. For a canyon width of 4 times the dam height, the mean error for the 2D estimate was reduced to zero for all moduli ratios. However, the variance was still significant. The maximum displacement predicted by a 2D model could be as much as 40% lower and higher than the 3D estimate, underlining the importance of the differences in the frequency response functions between the 2 and 3D models over the whole frequency range. The difference in the frequency content of the motions, coupled with the difference in the FRFs in the 0-10 Hz range, yielded considerably large differences between the 2 and 3D results for some motions. Similar to the mean value, the variance of the difference between the 2/3D results reduced with increasing canyon width as expected.

Table 3 Selected ground motions

ID	Event	Date	PGA (g)	PGV (cm/sec)	Magnitude	R_{jb} (km)	R_{rup} (km)	V_s30 (m/sec)
1	San Fernando	1971	1.238	114.413	6.6	0.00	1.81	2016.1
2	San Fernando	1971	0.205	12.836	6.6	21.50	21.50	969.1
3	Tabas- Iran	1978	0.862	123.341	7.4	1.79	2.05	766.8
4	Morgan Hill	1984	0.099	2.896	6.2	14.90	14.91	1428.1
5	Loma Prieta	1989	0.485	33.621	6.9	8.84	9.64	1428.1
6	Landers	1992	0.789	133.334	7.3	2.19	2.19	1369.0
7	Northridge-01	1994	0.159	14.631	6.7	15.11	20.29	1222.5
8	Northridge-01	1994	0.434	44.263	6.7	4.92	7.01	2016.1
9	Northridge-01	1994	1.585	103.332	6.7	4.92	7.01	2016.1
10	Northridge-01	1994	0.151	18.371	6.7	23.10	23.64	996.4
11	Kobe- Japan	1995	0.312	55.270	6.9	0.90	0.92	1043.0
12	Kocaeli-Turkey	1999	0.261	44.603	7.5	7.57	10.92	792.0
13	Kocaeli-Turkey	1999	0.230	38.271	7.5	3.62	7.21	811.0
14	Chi-Chi- Taiwan	1999	0.050	6.976	7.6	36.06	37.72	804.4
15	Chi-Chi- Taiwan	1999	0.091	10.867	7.6	53.30	56.93	789.2
16	Chi-Chi- Taiwan	1999	0.138	19.118	7.6	52.46	56.14	1525.9
17	Chi-Chi- Taiwan	1999	0.063	7.421	7.6	55.14	58.09	999.7
18	Duzce- Turkey	1999	0.053	9.978	7.1	25.78	25.88	782.0
19	Chi-Chi- Taiwan-04	1999	0.059	3.377	6.2	39.30	39.32	804.4
20	Chi-Chi- Taiwan-05	1999	0.036	3.439	6.2	44.36	45.03	789.2
21	Chi-Chi- Taiwan-05	1999	0.031	5.915	6.2	49.84	50.44	1525.9
22	Chi-Chi- Taiwan-06	1999	0.022	3.757	6.3	47.81	51.83	789.2
23	Chi-Chi- Taiwan-06	1999	0.039	8.785	6.3	52.33	56.02	1525.9
24	Loma Prieta	1989	0.443	95.728	6.9	3.22	5.02	1070.3
25	Tottori- Japan	2000	0.185	12.629	6.6	15.23	15.23	940.2
26	Tottori- Japan	2000	0.231	21.451	6.6	15.58	15.59	967.3
27	Parkfield-02	2004	0.245	14.605	6.0	4.66	5.29	907.0
28	Niigata- Japan	2004	0.143	2.643	6.6	52.15	52.30	829.0
29	Iwate- Japan	2008	0.085	5.044	6.9	37.45	39.41	829.5
30	Iwate- Japan	2008	0.289	26.246	6.9	16.26	16.27	825.8
31	Iwate- Japan	2008	0.093	2.679	6.9	56.72	56.72	934.0
32	Iwate- Japan	2008	0.227	5.419	6.9	40.42	40.43	849.8
33	Iwate- Japan	2008	0.184	4.290	6.9	57.15	57.15	859.2
34	Duzce- Turkey	1999	1.031	40.206	7.1	4.21	4.21	760.0
35	San Simeon	2003	0.047	8.762	6.5	37.92	37.97	1100.0

The results for the differences between the plane stress 2D models and the 3D independent monolith idealization was considerably different compared to the aforementioned case for a monolithic dam. The 2D displacement response was lower than the 3D counterpart. The significantly reduced peaks of the FRFs for this case were not matched by the 3D counterparts, especially for narrow canyons. Coupled with the frequency content of the motions, the 2D prediction underestimated the displacement response by around 25% (in the mean sense) for canyon widths of 2 to 6H for all moduli ratios. The demand predictions for independent monoliths from 2D analyses were significantly closer to 3D counterparts compared to the monolithic systems. Yet, for a given ground motion the maximum displacement predicted from a 2D analysis can be as low as 50% of the 3D analysis. The variance on the estimate followed the same pattern with the previous case, reducing with increasing canyon width.

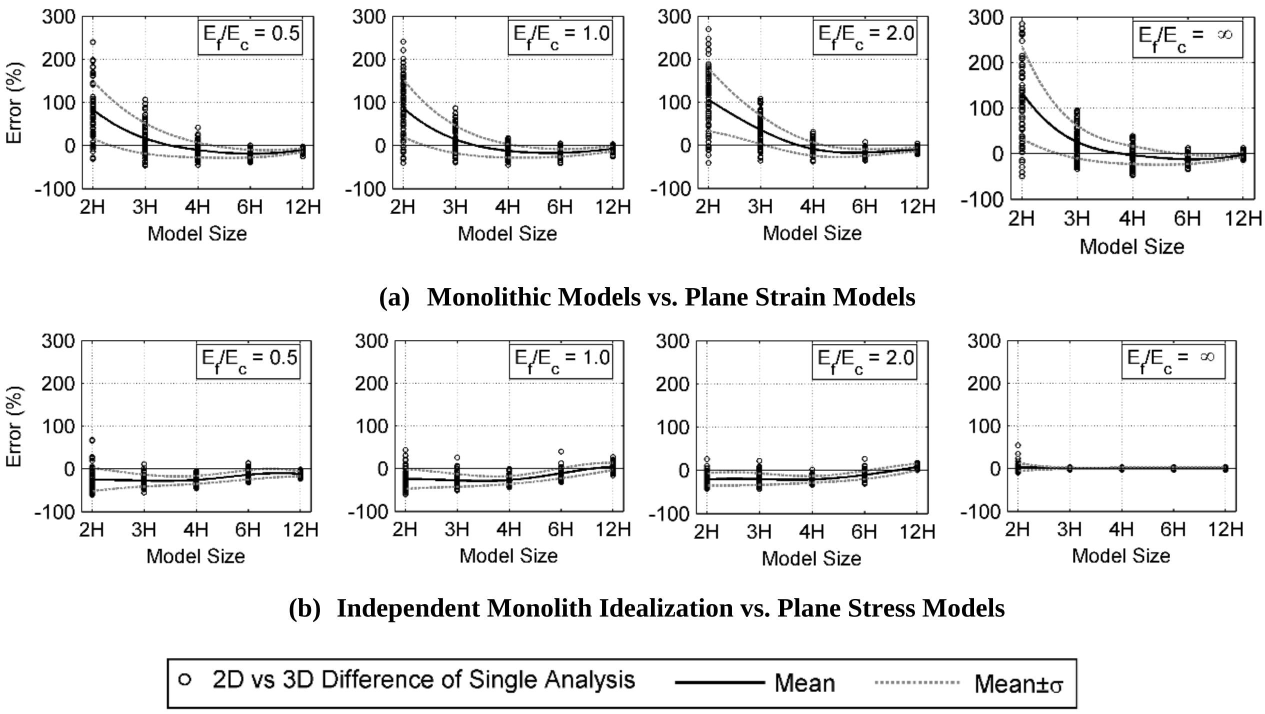


Fig. 6 Difference in the crest displacements, 2D vs. 3D models

The stress demand at the base of the dam is often critically important in order to decide on the damage expected on the dam system. Stress demands for the 2 and 3D models were computed at the toe of the dam. The stress values reported were obtained at the corner node on the upstream face of the dam at the center of the valley. The stress demands at the toe of the dam for the 2 and 3D models, compared using the same approach employed for the displacement demand, are presented in Fig. 7 separately for the monolithic and independent systems. For the sake of brevity, the mean±σ of the differences of the maximum principal stress between the 2 and 3D models are presented in the same chart for all moduli (E_f/E_c) and canyon width ratios (V/H). Following the same trend as displacements, 2D analysis of monolithic dams in a narrow canyon resulted in significant overestimation of the stress demands for the whole range of moduli ratios. The mean error in the stress estimate for a monolithic system in a canyon width of 2H was as high as 320% for the rigid base condition, reducing to 180% for the foundation/dam moduli ratio of 0.5. This error can be considered to be acceptably small only when the canyon width increased to 6H, six times the dam height. It is also observed that the mean error of stress predictions are almost two times the corresponding quantity for the crest displacement and can be as much as 3 times of the displacement error for the case of models on rigid foundations.

The analyses for the independent monolith case displayed a completely opposite trend as given in Fig. 7. The 2D analyses markedly underestimated the stress. For a moduli ratio of E_f/E_c=0.5, the 2D analysis underestimated the stresses consistently by around 40% for all canyon widths. Similar to the displacement predictions, the variance on the difference between the 2 and 3D analyses results was also substantially reduced, indicating the differences were obtained consistently with the same trend for the whole range of ground motions.

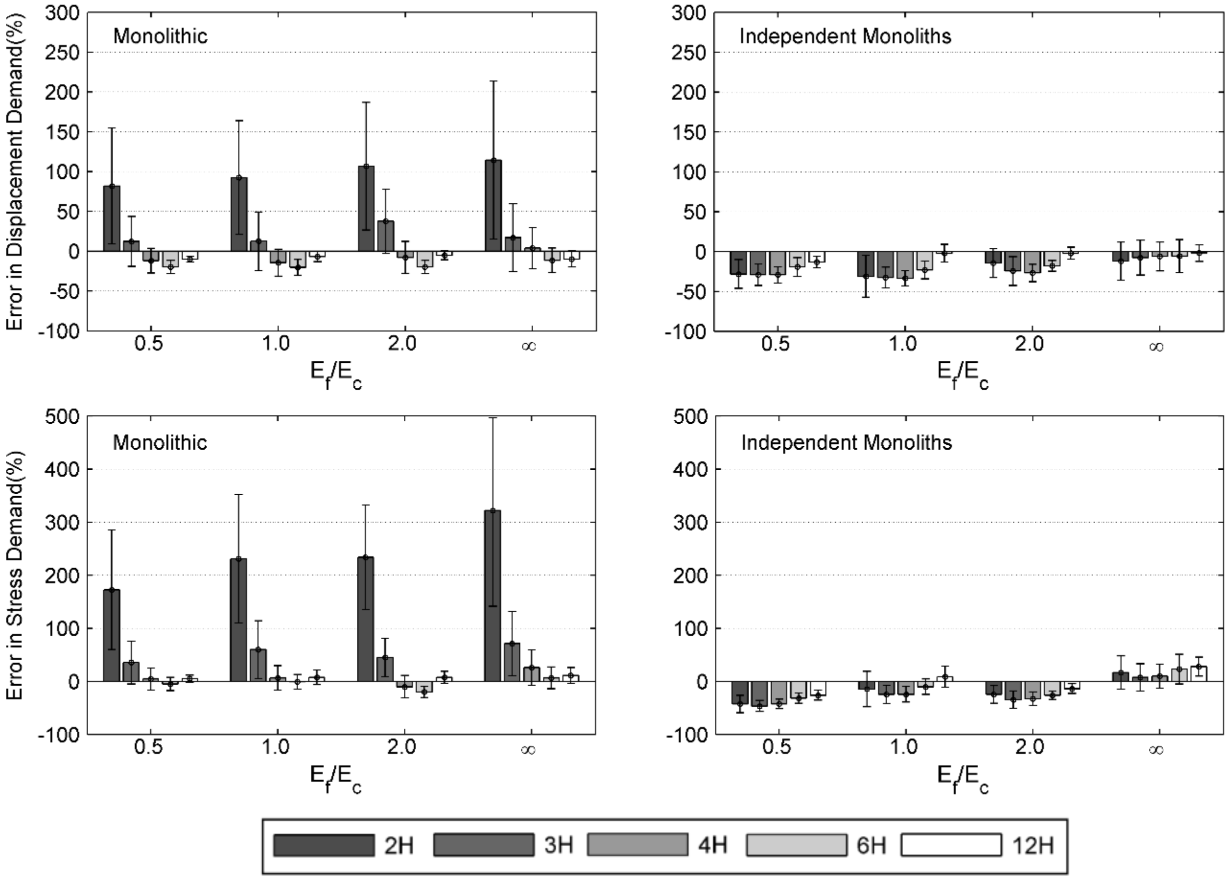


Fig. 7 Mean and Standard Deviation in Prediction of the response quantities, 2D vs. 3D models (w/reservoir)

The distribution of the stresses at the base of the dam is another issue of concern for gravity dams. In order to investigate the variability of the stress distribution at the base, the distribution at the base is presented for a single ground motion for a range of different canyon widths. The results are presented along the bottom of the center of the dam for both the monolithic system and the system comprised of independent monoliths for a foundation-structure moduli ratio (E_f/E_c) of 1.0. For the monolithic dam case, the stress distributions from the 2 and 3D models were similar; however, there were marked differences in the upstream and downstream maximum stresses. The stress distribution for the 2D plane strain model agreed well for the model with a 12H canyon width. For lower canyon widths, the stresses at the base were reduced following the pattern presented for the maximum principal stresses on the upstream face in Fig. 7.

For the case with the independent monoliths, the stress distribution between the 2D model and the 3D model in the largest valley were different, although agreeing well at the downstream face (+5m). The 3D stress distribution for the model in the widest canyon was lower than the 2D counterpart along the whole length of the base. For narrower canyons, however, the stress distributions for the 3D models were clearly above the 2D values. The results obtained were in parallel with Fig. 7, showing that the comparison of the maximum stresses given in this figure can be applied to the distribution of the stresses as well. It should again be noted that these results were obtained for a single ground motion, therefore, the difference between the distributions can be obtained much higher or lower as demonstrated by the differences in the maximum principal stresses presented in Fig. 7.

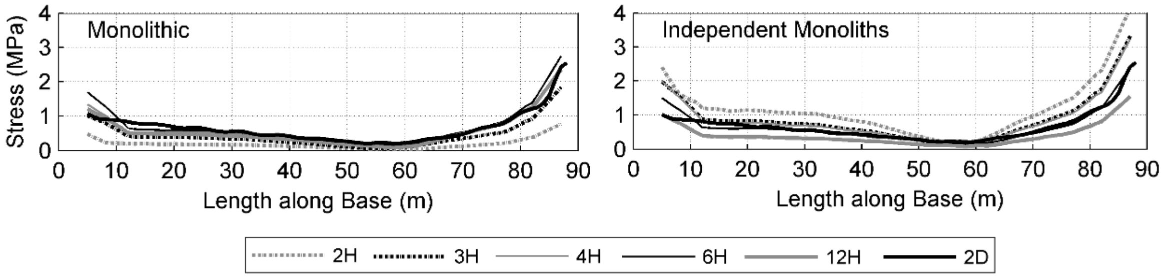


Fig. 8 The distribution of the maximum principal stress on the foundation

5. Summary and Conclusions

In this study, the common 2D analysis approach for determining the seismic demand on the concrete gravity dams were compared to the three dimensional counterpart using the rigorous DFRI formulations. A range of foundation-structure moduli (E_f/E_c) and height to width (V/H) ratios with the full reservoir condition were considered in order to determine the effects of the modeling choice on the design and evaluation of these systems. A total of 3360 time history analyses were conducted. The following conclusions can be drawn based on the results of the analyses.

- There was a significant difference in the fundamental frequency estimates for the 2D and 3D systems which was only alleviated for V/H and E_f/E_c ratios in excess of 6 and 2, respectively, for monolithic dam systems. A similar difference in the frequency estimate was observed for systems comprised of independent monoliths. The difference was reduced for V/H and E_f/E_c ratios greater than 4 and 2, a threshold slightly smaller than the former.
- For both the monolithic and independent systems, the differences between the 2 and 3D analyses' displacement predictions were significantly reduced only when the canyon width approached 6 times the dam height. However, the trend was very different. For the monolithic systems, 2D systems significantly overestimated the displacements, while for the systems comprised of independent monoliths, the reverse was valid.
- For the monolithic systems, the principal stress at the toe of the dam was predicted significantly higher with a 2D analysis for canyon widths lower than 6H regardless of the moduli ratio. On the other hand, for the system comprised of independent monoliths, the 2D model consistently underestimated the toe stress by as much as 40% in the mean sense. The 2 and 3D analysis get consistent with increasing canyon width and foundation rigidity.
- There was a significant dependency on the frequency content of the motion in obtaining the demand quantity as demonstrated by the large variance observed in the difference between the 2 and 3D results depending on the ground motion. This variance was substantially large for the monolithic systems and narrow canyons. For the systems comprised of independent monoliths, the variance was significantly lower.

The results of the analyses showed that except for the gravity dams constructed in very wide canyons, i.e. larger than 6 times the dam height, the predictions from the 2 and 3D analyses can be very different. This trend was valid for both the monolithic case and for systems built with independent monoliths. The 2D analyses yielded conservative results for the former, unconservative for the latter.. In conclusion, given the recent trend of RCC gravity dam construction for a wide range of canyon widths, the seismic effects need to be considered in a 3D configuration.

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