Comparison of 2D and 3D Seismic Analysis of Concrete Face Rockfill Dams in Narrow Canyons

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Abstract

Concrete Face Rockfill Dam (CFRD) is a type of rockfill dam with a concrete slab as its impervious part. CFRD is a popular choice in countries with high seismic activity because of its great flexibility under seismic loading and ease of construction especially in rainy regions. Seismic response of rockfill dams is usually evaluated through two dimensional dynamic analyses on the maximum cross-section of the dam. This type of analysis needs sufficient insight regarding the effects of canyon geometry on seismic behavior of dam. This 3D effect is the subject of this study. Using 2D and 3D FEM simulations, we have extracted maximum values of acceleration, displacements and stresses throughout dam body and face slab. Comparison of this results for different canyon geometries has resulted in interesting and useful findings about the effects of canyon geometry on CFRD's seismic behavior. The results indicate that in canyons wider than 5 times of the dam's height, 2D and 3D results have good compliance for a middle section of the dam. Results also show that in some geometries especially canyons with mild side slopes, the most critical section of the dam is not necessarily its middle section (section with the max height.

Keywords: Concrete Face Rockfill Dam, Dynamic Analysis, Canyon Geometry Effects.

1. INTRODUCTION

Concrete face rockfill dam (CFRD) is a popular choice in some countries because of its certain advantages over the clay-core earthfill and concrete dams. The structural and geotechnical design of CFRDs are based on precedence with little emphasis on using analytical tools to predict the performance of the face slab[1]. By ensuring the stability of the embankment using conventional slope stability analyses, the thickness of the face slab, as well as the reinforcement ratio, is usually chosen based on empirical formulas [2]. Recent cases of performance of rockfill dams under earthquake excitations show us that even though they are inherently resilient against dynamic forces due to their great flexibility, still some aspects of their behavior are not clear and have been subject of many researches for the last two decades. Understanding the behavior of a CFRD is a challenging task as the behavior is shaped by the complex interaction between various components of the dam, namely the rockfill, the cushion layer-face slab interface and the concrete face slab. Another important characteristic of a CFRD is the canyon's 3D geometry. The span of the canyon and the inclination angle of its slopes have a significant effect on the static and seismic behavior of a CFRD located in that canyon. In this paper, the aforementioned effect has been studied using 2D and 3D FEM simulation of different CFRD models. Comparison of the results of different analysis points out the effect of the canyon geometry on Dam's seismic behavior. In order to investigate the effect of 3D canyon geometry on CFRD's seismic behavior, 54 three-dimensional and 6 two-dimensional analyses have been implemented. These models are different is dam height, canyon span and abutment angle. Three different heights of 70, 100 and 130 meters have been used. Also for defining canyons geometry, the L/H parameter has been introduced in which L is canyon span and H is the height of the dam. For this study we have used 1, 3, 5 and 7 as different values for L/H. Another characteristic of dam that combined with height and L/H ratio completely defines the dam's geometry, is abutment angle (the angle between canyon side slope and horizontal imaginary plane). In this study we've used the abutment angle of 63 degrees for L/H=1 ratio, 45 and 60 degrees for L/H=3, and 30, 45 and 60 for both L/H=5 and L/H=7. For 2D models, we just had the variable of dam height for which we used 70, 100 and 130 meters. In summary, there are 27 different 3D and 3 different 2D geometries. We investigated the seismic behavior of these models under two different earthquakes which resulted in 54 three-dimensional and 6 two-dimensional FEM seismic analysis respectively.

2. FEM MODELING

Simulation of CFRDs under seismic loading has been implemented using a FEM commercial software. All models include static and dynamic stages with comprehensive attention to the construction and impounding phases. All the intricate details of FEM seismic analysis of geostructures is taken into account in this study. Followings are the number of most important features of FEM models used in this study:

2.1. GEOMETRY

Figure 1 shows an example of 2D and 3D geometries used for seismic analysis of the CFR dams. For 3D models, in order to decrease the analysis time of the FEM software, half model has been used. Since the 3D dam model is symmetrical with respect to the river axis and also the seismic excitation is being imposed parallel to the river axis, using half model is completely warranted.

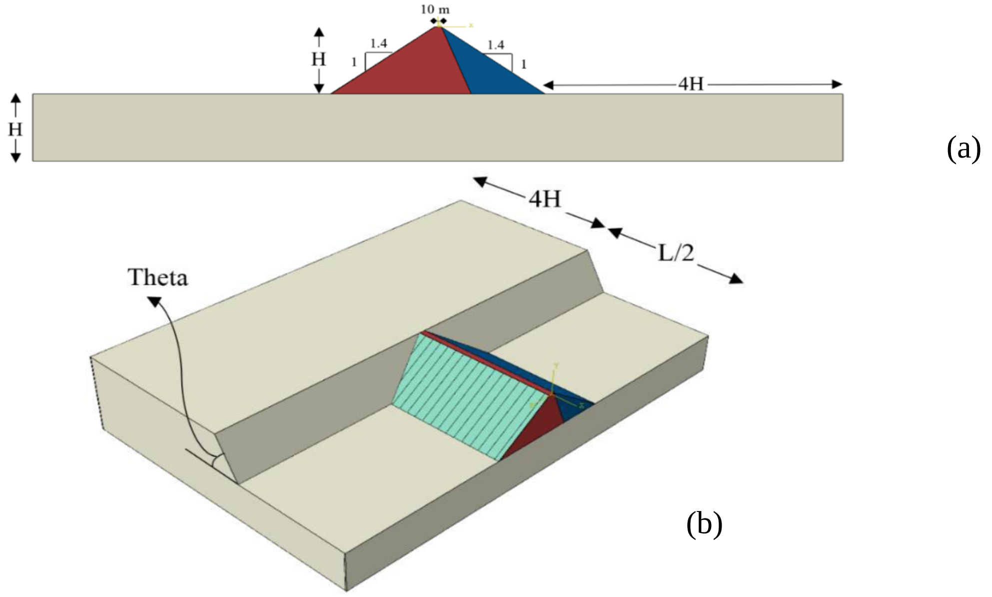

Figure 1- 2D (a) and 3D (b) FEM models of CFRD

2.2. MATERIAL PROPERTIES

For foundation and abutment, properties of good quality rock have been used as is the case with most CFRDs. For rockfill materials typical CFRD properties have been used and finally for face slab, the properties of a reinforced concrete with compressive strength of 24 MPa was inserted in the model. Material properties for different parts of dam models are summarized in Table 1. The other important aspect of dam materials are their constitutive models. In this study three different constitutive models have been used. For foundation and abutment, we have used elastics model because of rock's high stiffness. For rockfill material that constitutes dam body, we have used the elastic-perfect plastic Mohr-Coulomb model which takes into account the plastic strains of rockfill materials under loading. The most important part of the CFRD is face slab, so special emphasis has been put on its constitutive model.

Table 1- Material Properties

Zone	Density (kg/m^3)	Young Module (MPa)	Poisson Ratio	Cohesion (kPa)	Friction Angle (˚)	Dilation Angle (˚)
Face Slab	2640	31000	0.2	-	-	-
Foundation and Abutment	2500	20000	0.25	-	-	-
3B (Red area in Figure)	2100	200	0.35	0	50	15
3C (Blue area in Figure)	1900	150	0.35	0	45	10

We used the state of the art Plastic-Damage model for face slab [3]. This model completely simulates the complex behavior of the reinforced concrete under cyclic loading and takes into account the stiffness degradation of the concrete resulted from cracks created. Another important dynamic property of materials is their damping. Damping of material in this study has been introduced into models using Rayleigh's α and β coefficients [4].

2.3. INPUT EARTHQUAKE RECORD

The 1983 earthquake of Coalinga in California with magnitude of 6.4 has been selected as an excitation input. Two different versions of this record have been used in seismic analysis with their max acceleration scaled to 0.3g and 0.6 g.

Figure 2 [5] shows the acceleration record of this earthquake with maximum acceleration of 0.3g.

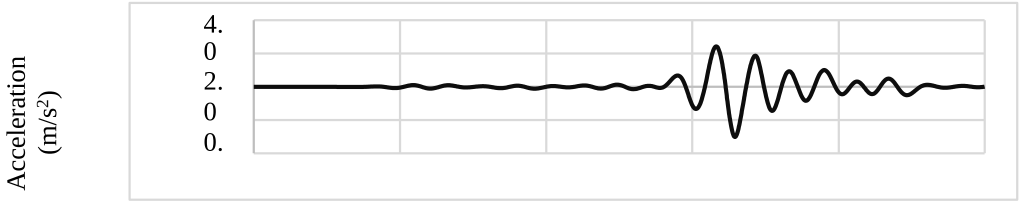

Figure 2- Acceleration Record of Input Earthquake with Peak Acc. Equal to 0.3g

2.4. BOUNDARY CONDITIONS

From wave propagation theories we know that waves tend to reflect upon reaching a boundary. Using conventional rigid boundaries in dynamic analysis, raise this problem in FEM analysis. After earthquake waves reach model boundaries, they reflect toward center of the model and cause extra strains and deformation. In reality we do not encounter this phenomenon because there are no such boundaries in vicinity of a real dam. One way to overcome this problem is to increase the distance between dam and model boundary which is not applicable to most of the cases since it makes the model too large for FEM dynamic analysis. Another way and the one used in this study, is introducing viscose dashpots at model boundaries to absorb coming waves and prevent them from returning to the dam body. Therefore, two perpendicular dashpots have been added to the model boundaries using suggestion of Lysmer [6] for their damping properties.

2.5. INTERACTION

Considering the construction stages of CFRD, we know that face slab and body parts of dam are not completely connected and they can move relative to each other. Also the face slab is not continuous itself and consists of a number of vertical segments. Therefore, interaction properties had to be introduced into the models. The friction coefficients have been set equal to μ=0.5 and μ=0.7 for slab-rockfill interaction and slab-slab interaction respectively [7].

3. THE EFFECT OF DAM HEIGHT ON SEISMIC BEHAVIOR

The height of a dam plays an important role on its seismic response since it affects dam flexibility and hence changes its fundamental frequency. Using 2D finite element analysis we've calculated natural frequency of a CFRD with three different heights and also extracted their seismic response under two different seismic excitations. The Type 1 earthquake record has dominant frequency of 4.16 Hz and maximum acceleration equal to 0.3g while the Type 2 earthquake has the dominant frequency the same as Type 1 earthquake but with maximum acceleration of 0.6g. The extracted data have been summarized in Table 2 for both Type 1 and Type 2 excitations.

Table 2- Seismic Response of 2D CFRD Models

Dam's Height (m)	Dam's Natural Frequency (Hz)	Max. Acceleration of Crest (m/s^2)		Dominant Frequency of Dam's Response (Hz)	
		E.Q. Type 1	E.Q. Type 2	E.Q. Type 1	E.Q. Type 2
70	0.866	6.13	7.45	4.16	4.16
100	0.630	5.34	7.05	3.84	3.84
130	0.488	2.80	4.69	3.22	3.22

According to Table 2, it can be deduced that increasing dam's height will result in lower natural frequency or higher natural period. In other words, increasing dam's height makes the dam body more flexible. Results from Table 2 show that more flexible dams undergo a lower acceleration. This phenomenon can be justified using the frequency content chart of input earthquake. It is evident from Figure 3 that around dam's natural frequency values, as we decrease the frequency, the spectral acceleration will decrease.

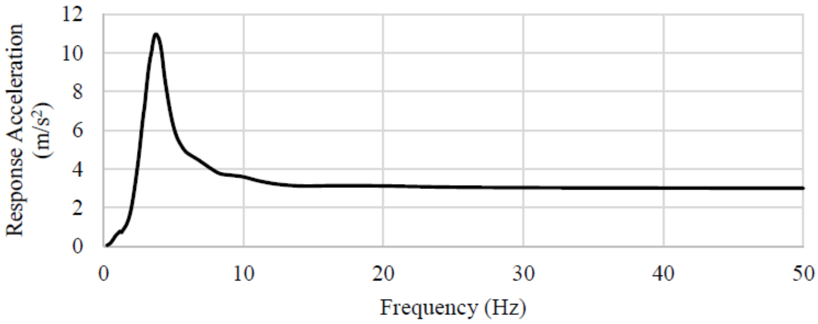

Figure 3- Spectral Acceleration of Type 1 Earthquake (Peak Acc. Equal to 0.3g)

4. THE EFFECT OF CANYON GEOMETRY ON FUNDAMENTAL FREQUENCY

Canyon Width, is a key factor in seismic response of dams. CFR dams located in wide canyons show different responses compared to dams located in narrow ones. Because of the confinement and stiffening effect of the narrow canyons, the fundamental natural periods of CFRDs with the same height vary with varying canyons width. Results show that studying the effect of canyons geometry on dam's response is best regulated using the parameter L/H)the ratio of canyon's width to dam's height). We extracted the fundamental period for different dams with different canyons geometries and the results are shown in Figure 4. It can be seen that increasing the L/H ratio (widening the canyon) results in reduction of the dam system's natural frequency. In other words, as we make the canyon wider, the dam behaves in a more flexible manner and this means lower frequency. Forthuremore, 3D frequency of dams with any geometry is always higher than its 2D frequency, which indicates that canyons always have stiffening effect.

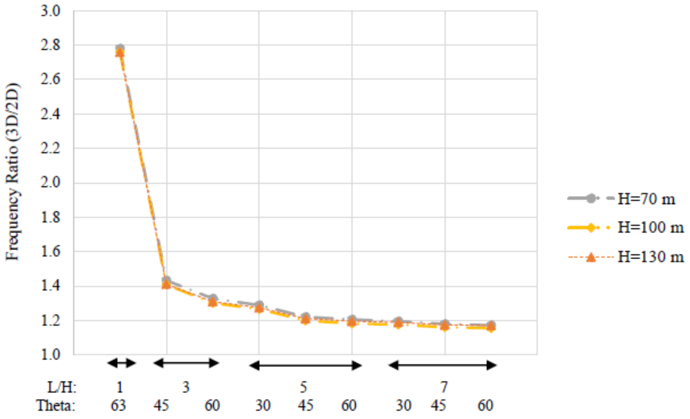

Figure 4- Effect of Canyon Geometry on Fundamental Frequency of CFR Dams

5. THE EFFECT OF CANYON GEOMETRY ON THE SEISMIC BEHAVIOR OF DAM BODY

Seismic behavior of dam body in CFR dams includes accelerations, displacements, strains, etc. In this study, horizontal acceleration and horizontal displacement of different dam models, have been presented. Two type of comparison has been made between results for better illustration of the differences between 2D and 3D behavior of the dam under earthquake excitation. In one type, we've compared the maximum values of acceleration (ordisplacement) at crest for 2D models with values at crest (middle canyon section) in 3D models. This way we can verify with what accuracy, 2D models represent 3D behavior of dams. In another type of comparisons, we've extracted maximum values throughout whole dam and have compared it with max values from 2D analysis and max values from middle section of 3D analysis. This second type of comparison, illustrates the real 3D behavior of dam and the fact that in some cases of CFRDs under seismic loading, the middle section of dam, is not necessarily the most critical section.

5.1. MAX VALUES OF HORIZONTAL ACCELERATION

Figure 5 shows that dam with L/H greater than or equal to 5, have good conformity between 2D and 3D models. Also from Figure 66 we understand that max horizontal acceleration of dam body does not necessarily occur in middle section of dam. This is especially noticeable in dams located in canyon with low Theta.

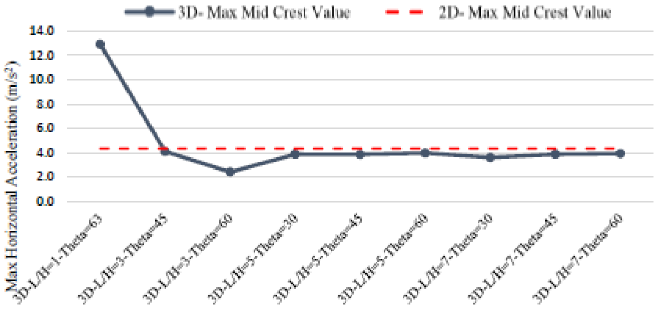

Figure 5- Comparison of 3D and 2D Results for Max Dam Crest Horizontal Acceleration at Middle Section under PGA=0.3g Earthquake

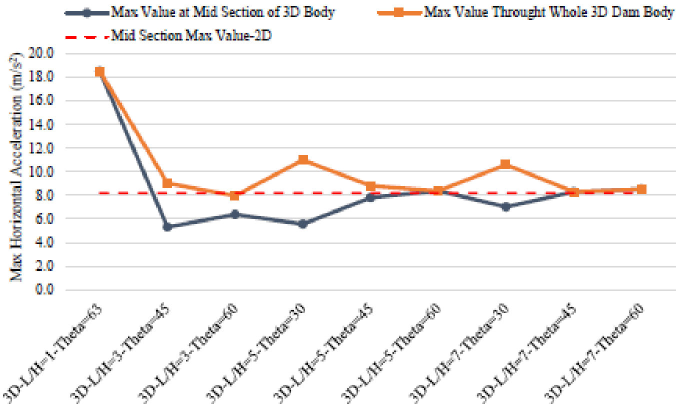

Figure 6- Comparison of Max Horizontal Acceleration Value at Different Locations of Dam Body for 3D and 2D Analysis under PGA=0.3g Earthquake

5.2. MAX VALUES OF HORIZONTAL DISPLACEMENT

Except for the dam with triangular section (L/H=1), according to Figure 7 results of the max horizontal displacement from 2D and 3D models are quit identical.

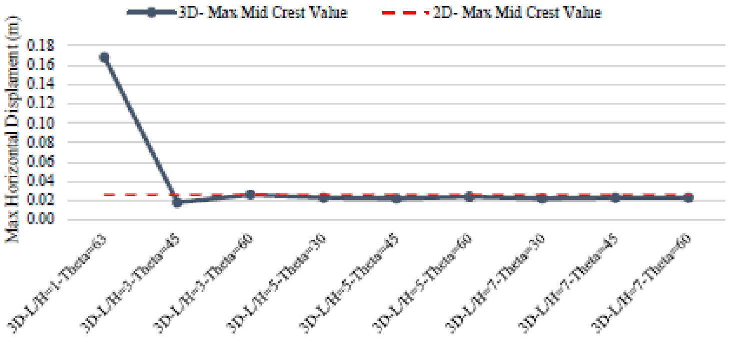

Figure 7- Comparison of 3D and 2D Results for Max Dam Crest Horizontal Displacement at Middle Section under PGA=0.3g Earthquake

Figure 8 gives us another interesting aspect of dam's behavior. It shows that even though the max 2D and 3D results comply in middle section, still the max value occurs someplace other than middle section. In this particular case it occurs near abutment. So we find out that sections with max height do not necessarily give the most critical results.

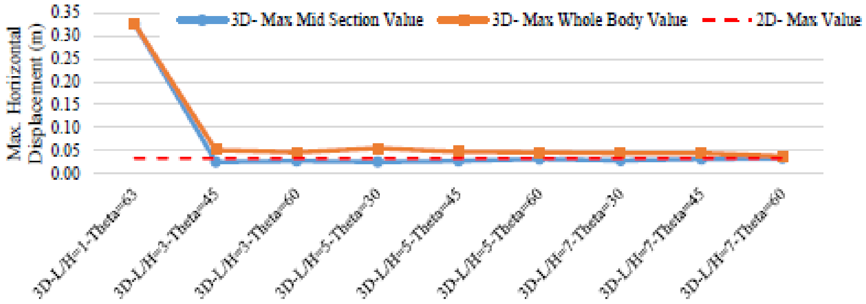

Figure 8- Comparison of Max Horizontal Displacement Value at Different Locations of Dam Body for 3D and 2D Analysis under PGA=0.3g Earthquake

6. THE EFFECT OF CANYON GEOMETRY ON SEISMIC BEHAVIOR OF FACE SLAB

The most important section of CFRD is its face slab, so its behavior is crucial to dams' safety and performance. Seismic loading of the dam induces compressive and tensile stresses in face slab that may result in its rupture and failure. In this study we extracted maximum compressive and tensile stresses in face slab in 2D and 3D models. Figure 9 shows that canyon geometry affects max tensile stresses induced in face slab. Its effect is more intense in lower half of the slab where higher water pressure does not allow slipping of the slab relative to the rockfill. Also 2D models tend to underestimate the max tensile stress at bottom of the dam. Figure 9 illustrates the max compressive stress of face slab. There is good compliance between 2D and 3D results. But again dam located in triangular canyons behaves completely different from other geometries. Higher values in dam with L/H=1, can be explained considering stiffening effect of very narrow canyon. In this narrow geometry, slab is completely confined between hard rock boundaries and this cause it to undergo high stresses.

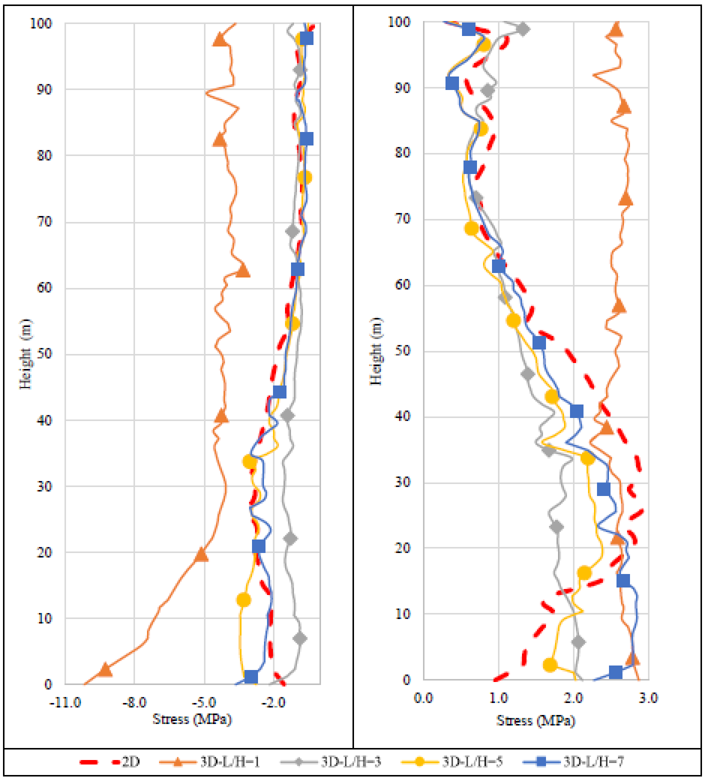

Figure 9- Maximum Compressive Stress (Left) and Tensile Stress (Right) of Face Slab

7. CONCLUSIONS

- Increasing dam’s height results in more flexible dam structure which yields lower fundamental frequency. Increasing L/H ratio has the same effect. Change in fundamental frequency has significant effect on dam seismic behavior.
- 3D analysis always shows higher frequency that 2D analysis for a dam with the same height. Also the ratio of 3D frequency to 2D frequency for a specific L/H ration does not depend on dam’s height.
- Results of max horizontal acceleration developed in dam body shows that for dam geometries with L/H ratio higher than or equal to 5, for middle section of dam body, 3D and 2D analysis concur. On the other hand, for dam with L/H=1 and other with canyons slope angle (Theta) equal to 30˚, the highest acceleration does not occur within middle section of the dam. In other words, in some geometries, the most critical section is not necessarily the middle section. Result of the max horizontal displacement of dam body also confirm this statement.
- From results of the max compressive and tensile stresses induced in face slab, it can be deduced that stresses in lower half on slab is more sensitive to the canyon geometry. Also 2D analysis tend to underestimate the max tensile stress in this part of the slab. For compressive stress, 2D and 3D analysis are in great agreement except for triangular geometry (L/H=1).
- For dam with L/H ratio equal to 1, very narrow geometry of canyon results in more confinement. Slabs that are confined show more stiffness and undergo higher stresses.

8. REFERENCES

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