Seismic Performance Evaluation of Karun III Double Curvature Arch Dam Considering the EffectsofNon-uniform Excitation

FatemehEsmailiSoureh*[,1], Alireza Manafpour[2], Mohammad Manafpour[2]
1, 2-Department of Civil Engineering, Urmia University

F.esmaili.68@gmail.com

Abstract

Arch concrete dams are among the most important infrastructures in supplying sustainable water in a country. Due to their importance and the heavy construction costs, it is vital to study their behavior, especially under earthquake loads. In this type of large structures, owing to the presence of extended supports, seismic movements of the ground at different points in the structure-foundation intersection can be considerably different. Due to the analytical complexitiesin the design of concrete arch dams, non-uniform excitations are not commonly considered. The main objective of this study is to accurately evaluate the seismic performance of the dam due to non-uniform excitation. In this paper, seismic movements recorded on 2007/11/20 by instruments installed in various positions at the intersection of dam and foundation of Karun III double arch concrete dam are used for this analysis.Additionally the study includes a simulated non-uniform seismic event based on the Northridge earthquake and time delays from one of the recorded actual ground motions in the site.The results of numerical analysis carried out with real records show that by applying non-uniform excitations, there exists a meaningful difference in the dam responses in terms of displacement and stresses. It was also shown that the non-uniform effects increase the maximum displacement values in the central block and it is also increases by seismic intensity level. The general pattern of displacement in both modes of excitation, at each level of seismic action is similar. The maximum tensile stress in both the uniform and non-uniform stimulation occurs in upstream at the intersection of body and foundation and its extent becomes wider in the non-uniform case. Maximum compressive stress in both of the stimulations occurs in the upstream face in the central part of the body and extends to the crown with increasing seismic level. In downstream of the dam body the maximum compressive stress is located at the lower part of the dam and foundation intersection. These results indicate the importance of non-uniform excitation in the dynamic analysis of arch concrete dams.

Keywords: Non-uniform excitation, Double curvature dam, linear dynamic analysis, Karun III dam.

1. INTRODUCTION

Dams are significant structures that considered in strategic structures area in terms of their key role for supply of potable water, agriculture, and water production. Therefore, it is important to identify all the parameters that affect the safety of dams. Earthquake load is one of the most important parameters to be considered in the planning and analysis of these important engineering structures. Long arch dams are exposed to the effects of spatially varying motions during an earthquake. Earthquake support vibration was sometimes not similar due to wave publication in different directions and change amplitude, phase and frequency content that has the main effect on long structures security during a huge earthquake. Factors affecting ground motion characteristics are derived from the three mechanisms of the effect of wave crossing, the effect of incoherence, and the effect of local response. Non-uniform motions have received less attention due to the analytical complexity in the usual design of these structures. Whereas recent studies show that attention to non-uniform stimuli is necessary to accurately assess dam seismic safety.

In recent years, few dams have been equipped with accelerometers. Accelerometers are installed on dam contact surface and foundation and record earthquake movements at various positions. Alves and Hall (2006) investigated the effects of spatially varying stimuli on the nonlinear response of the Pacoima Dam using seismic data recorded by the Dam Accelerometer Network. The results showed that the stresses along with the anchors and in the central part of the downstream were higher in non-uniform excitation. Chopra and Wang (2010) calculated the responses of two dams to variable ground motions recorded during an earthquake in a linear fashion considering the dam-water-rock interaction. They conclude that the effect of time-varying motions for one dam can vary from one earthquake to another, depending on its focal depth and distance from the dam site. In two similar works, Ghaemian and Sohrabi-Gilani (2012) examined the responses of Pacoima and Karun III dams to spatial variable motions. He studied topographic resonance between different points of the contact surface by obtaining ratios of displacement and pseudo-acceleration response spectra. The acceleration recorded at different stations at the joint dam-foundation boundary was used for non-uniform motions and the base station acceleration was used for uniform excitation. The results showed that non-uniform stimulation could have severe effects on barrier behavior and increase responses. Tarinejad et al (2013) investigated the response of the Pacoima arc dam to the non-uniform stimuli generated by the seismic wave propagation model. Non-uniform ground motions were generated based on a single record available at one site and wave propagation analysis. The Chino Hills (2008) earthquake records were used at the Pacoima Dam site to demonstrate the accuracy of this method. Significant increases in stresses were observed especially near the foundation and different patterns of stress distribution for non-uniform stimulation compared to uniform stimulation. Mirzabozorg et al (2013) investigated the seismic response of the Dez dam-reservoir-foundation system to varying ground motions. They used the Monte Carlo method to generate non-uniform motions. The results showed that non-uniform stimulation increases the structural responses of the dam. Akbari et al. (2015) examined the linear response of arch dams to non-uniform stimuli concerning the effects of charge composition.

2. KARUN III DAM

Karun III Dam and Power Plant (Fig. 1) is a two-arched concrete dam located on the Karun River, 28 km east of Izeh city in Khuzestan-Iran province. The height of the dam is 205 m from the bottom of the dam, the length of the crest is 462 m, the width of the dam crest is 5.5 m and the width of the lowest level is 29.5 m. One of the most important goals of the Karun 3 project is to generate 4172 million kWh of electricity annually and provide the country with the most electricity needed. In addition, controlling the floods and high water of the Karun River to prevent damages to the Khuzestan Plain and downstream cities and annually adjusting about one billion cubic meters of water to irrigate about 12,000 hectares of downstream farmland is another objective of the Karun 3 Plan.

Figure 1: View of Karun 3 Dam and Power Plant

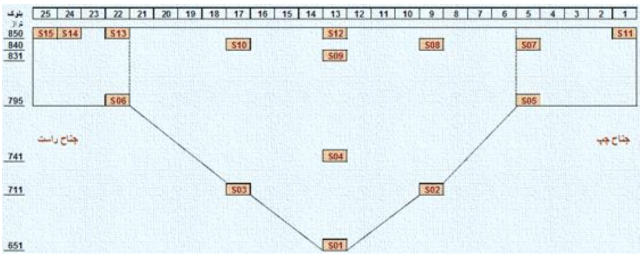


Figure 2: Layout of the accelerometer in Karun Dam 3

3. KARUN III DAM ACCELEROMETER NETWORK

Accelerometers are tools that measure the rate of acceleration of dam body structures by induced and natural earthquakes. In the Karun III Dam, 15 accelerometers are installed in various parts of the body and supports to investigate dam responses and the characteristics of recorded earthquakes that all of them are transferred central reading station in the dam control building in the crown block 25 with the help of communication cables. Figure 2 shows the layout of the various accelerometer channels in the Karun III Dam.

As they are shown in Fig. 2, channels S01, S02, S03, S05, S06, S07, S11, S13, S14, and S15 are located in the adjoining blocks and the joint boundary of the dam and foundation and the channels S04, S08, S10, S09 and S12 inside the dam body and can measure and record seismic motions in three directions.

4. MODIFICATION AND SCALE OF RECORDS RECORDED AT THE DAM SITE

Since there was no significant earthquake in dam exploitation period and the recorded records have very poor seismic characteristics compared to earthquake dam design, therefore, an earthquake occurred on 20/11/2007, which is one of the most important seismic movements recorded at the dam site, was selected, modified, scaled and used for analysis. The characteristics of this earthquake are presented in Table 1.

Because the received records were crude and no corrections were made, they were corrected for eliminating high-frequency errors by 5-order Butterworth filtering and in the frequency range 0.3Hz-30Hz with

Seismo Signal software. As noted above, the recorded seismic movements are weak and are not very useful for examining the important seismic effects on the dam directly. Different methods of scaling can be used, but in this paper, we have attempted to scale seismic movements recorded by the dam site response spectrum (Fig. 3) in a similar manner to the standard 2800 method at three seismic hazard levels to preserve the frequency properties according to Figure 4. The frequency of Karun 3 dam structures was obtained 1.63 Hz and the records were scaled in the period of 0.2T-1.5T. According to the standard 2800 scale method, the acceleration response spectrum of the record in the 0.2T-1.5T period range corresponds to or exceeds a specified approximation to the spectrum of the site. The scale coefficients obtained are presented in Table 2.

Table 1: Selected earthquake characteristics

Date	Magnitude	Depth	Earthquake Center Coordinates	
	ML	km	Longitude	Latitude
2007/11/20	4.9	17.0	50.10E	31.65 N

Table 2: Scale coefficients of earthquake records

Record scale coefficient 2007.11.20	LEVEL
4	DBE
7	MDE
10	MCE

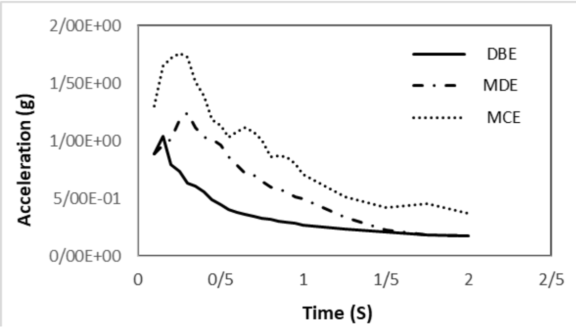


Figure 3: Response spectrum at three risk levels in the horizontal direction

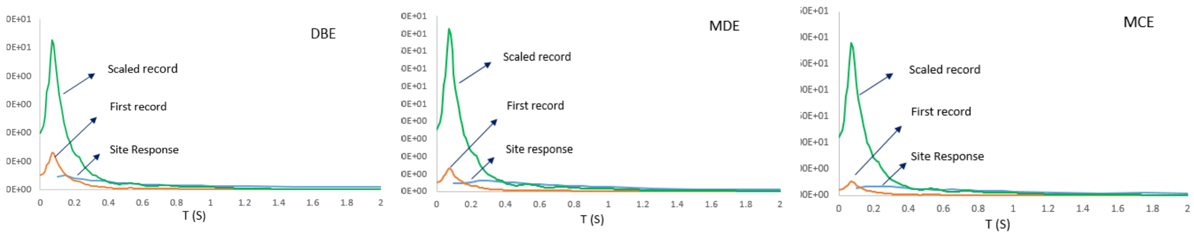
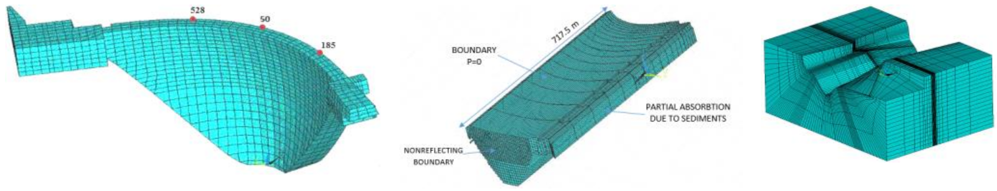


Figure 4: Scale the records with the spectrum of the building according to the 2800 code at three levels of risk

5. FINITE ELEMENT MODEL

The finite element model of the Karun III Dam has been modeled and calibrated by Mirzabozorg et al. For modeling the body, the coordinates of the main body of the dam and its vertical and vertical arc characteristics in different scales were extracted from the existing maps. The length of the reservoir used in the numerical model is considered to be appropriate for the damping of its end effects in seismic analysis. Accordingly, the length of the reservoir was considered to be 717.5 m, which is about 3.5 times the height of the dam. It is worth noting that the tank is modeled as a fixed-section prism. According to the specific topography of the area, the foundation model is considered to be twice the height and width of the dam in all directions. Figure 5 shows the different parts of the dam-lake-foundation finite element model. The number of elements in the body of the dam is 3958, in the foundation is 21848 and in the reservoir is 2302. Table 3 shows the parameters for the foundation, concrete, and tank in the present numerical model.



c) b) a)

Figure 5: Finite Element Model a) Dam body, b) Reservoir environment with boundary conditions, c) Rock foundation

Table 3: Foundation, Concrete, and Reservoir Water Parameters Used in Finite Element Model

Foundation	
Modulus of foundation elasticity	14 GPa
Foundation Poisson's coefficient	0.2
Body concrete	
The specific weight of concrete	2400 kg/m3
Modulus of elasticity of concrete	30 GPa
Poisson coefficient of concrete	0.2
Reservoir	
Density of water	1000 kg/m3
Speed of sound in water	1437 m/s
The wave absorption coefficient for the tank wall and floor	0.11
The wave absorption coefficient for the far end of the tank	1

Since the actual size of the reservoir is very large, in reality, the waves created during the earthquake in the reservoir move to the far end of the reservoir and die in their path. Therefore, the distal end of the reservoir should be considered as the boundary that absorbs the waves completely. This boundary condition is based on the assumption that the waves propagate in a flat form upstream of the dam.

6. NON-UNIFORM EXCITATION

The non-uniform and asynchronous nature of the records is evident by viewing and viewing the recorded records. To apply the earthquake acceleration in a non-uniform manner, the contact surface of the dam and foundation is divided into six parts according to Figure 6 and modified records for the same stations at three levels of danger were applied to these areas. The S01 station record located at the dam-Pi boundary and at the three DBE, MDE, and MCE hazard levels were applied to the joint dam-pi level nodes to apply the earthquake acceleration uniformly.

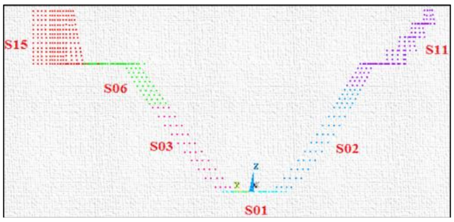


Figure 6: Segmentation of Common Border Nodes

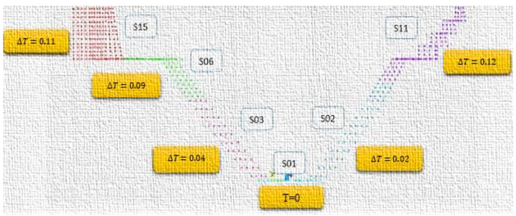


Figure 7: Time difference of records in different alignments compared to station record S01

7. NORTHRIDGE EARTHQUAKE

The earthquake records from the dam site that occurred on 2007.11.20, despite being one of the most important seismic movements recorded at the dam site, but with a significant magnitude earthquake not yet recorded at the Karun 3 Dam site, the existing records are poor in energy content and scalable to the DBE, MDE and MCE earthquakes of the Karun 3 Dam. However, given the realities of seismic movements recorded at different stations, they are valuable and in previous sections, attempts have been made to scale non-uniform effects by scaling these earthquakes. Therefore, this section uses a well-known and strong seismic record (Northridge earthquake) whose characteristics are presented in Table (4) and Figure (6). However, the actual motion has been modeled before to simulate a non-uniform motion. That is, it is assumed that seismic movements at different stations of the dam have similar motions but differ in time to reach the desired station.

Accordingly, the time difference recorded in the 2007 earthquake was applied as a non-uniform motion by the acceleration mappings according to Fig 7.

Table 4: Northridge earthquake characteristics

Date of occurrence	Large (Richter)	Depth (kilometer)	Coordination
1994/1/17	6.7	18	34.216North - 18.537West

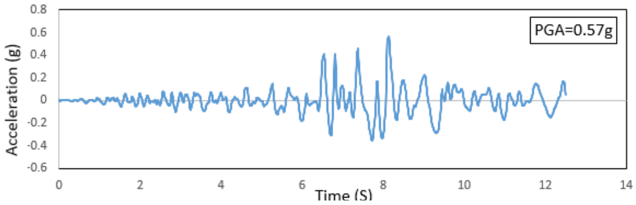


Figure 6: Northridge earthquake record in the horizontal direction

8. Analyze the results

9. Numerical model validation

The earthquake that occurred on 2007.11.20 was used to validate the present model. Since all stations recorded seismic movements at the time of the earthquake, the S12 station located at the central crest of the crest at level 850 was used to check the recorded displacement. Figure 8 shows the time history of displacement in three directions of Stream, Cross-Stream and Vertical according to numerical model data as well as values recorded at station S12. Despite some differences, good agreement is observed between the numerical results and the actual values recorded in the earthquake.

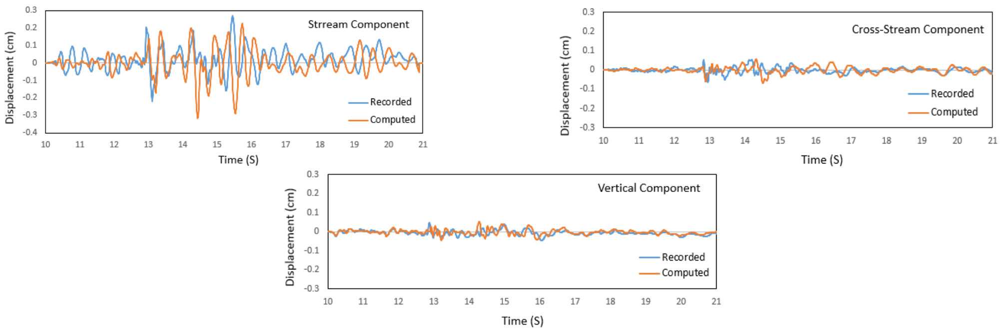
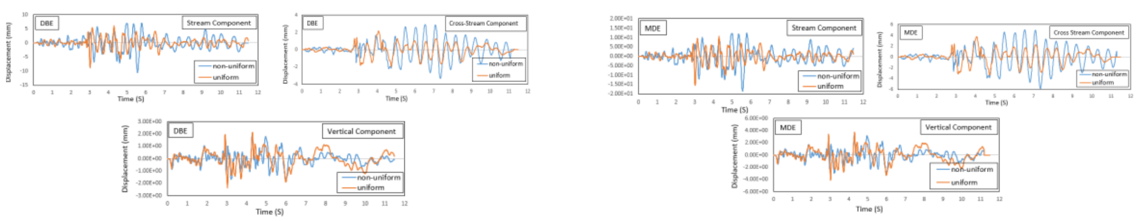


Figure 8: Recorded and calculated displacements in the direction of Stream, Cross-Stream and Vertical at Level 850

Although there is a good agreement between the recorded and calculated displacement time histories in three directions, these values are not fully consistent, that this could be not unexpected due to the limited number of earthquake recording stations and assumptions about seismic motion in adjacent stations, differences in material properties with actual values, and uncertainties in acceleration data recording and processing methods.

10. DisplacementOf Earthquake 2007

In this section, the timing histories of the displacement of the central canopy node (node 50-Figure 5-A) for two uniform and non-uniform ground motions at three seismic hazard levels are shown and compared in figure 9 and table 5.



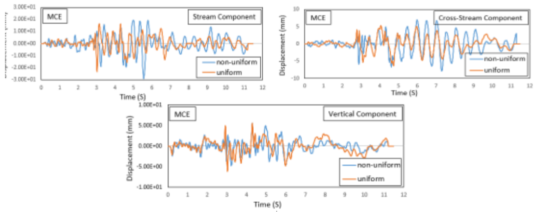


Figure 9: Comparison chart of the time history of displacement response in the stream, cross-stream and vertical directions in the central corona node in two uniform and non-uniform states at the DBE, MDE and MCE hazard

Table 5: Maximum displacement values for the central crown ax for the 2007.11.20 record

Earthquake level		Max Displacement (mm)					
		Towards Down-Stream (-)			Towards Up-Stream (+)		
DBE	Node 50						
	Directions	Stream		Cross-Stream		Vertical	
	NON-UNIFORM	-10	7	-2.83	2.56	-1.72	2
	UNIFORM	-8.8	6.1	-2.2	1.8	-2.4	2.13
	Variation (%)	13.6%	14.7%	28.6%	42.2%	-28.3%	-6.1%
MDE	Directions	Stream		Cross-Stream		Vertical	
	NON-UNIFORM	-18	12	-5	4.45	-3	3.6
	UNIFORM	-15	11	-3.75	3.2	-4.2	3.7
	Variation (%)	20%	9.1%	33.3%	39.1%	-28.6%	-2.7%
MCE	Directions	Stream		Cross-Stream		Vertical	
	NON-UNIFORM	-29	19	-8	7	-4.7	5.6
	UNIFORM	-24	16	-6.34	5.32	-6.1	5.63
	Variation (%)	20.8%	18.7%	26.2%	31.6%	-22.9%	-0.5%

As can be seen in Figure 9, the general pattern of displacements is the same at three hazards. According to Table 5, at the three levels of risk, the displacement values in the upstream and downstream directions in the non-uniform excitations are more than uniform, and these values increase as the earthquake hazard level increases. As can be seen, the rate of increase in displacement in non-uniform motions relative to uniform motions varies from 14 to 20.8% depending on the seismic level and generally increases with increasing seismic intensity. According to Table 5, the maximum displacements are in the uniform and non-uniform stimuli and downstream of the three risk levels.

11. NORTHRIDGE EARTHQUAKE DISPLACEMENT

The positioning of the investigated nodes is shown in Fig 5a. Fig 12 shows the time history diagram of the displacement of the central crown node (node 50) and a quarter of the right support (node 528) and a quarter of the left support (node 185) and table (6) of the maximum displacement values upstream and downstream for the nodes examined.

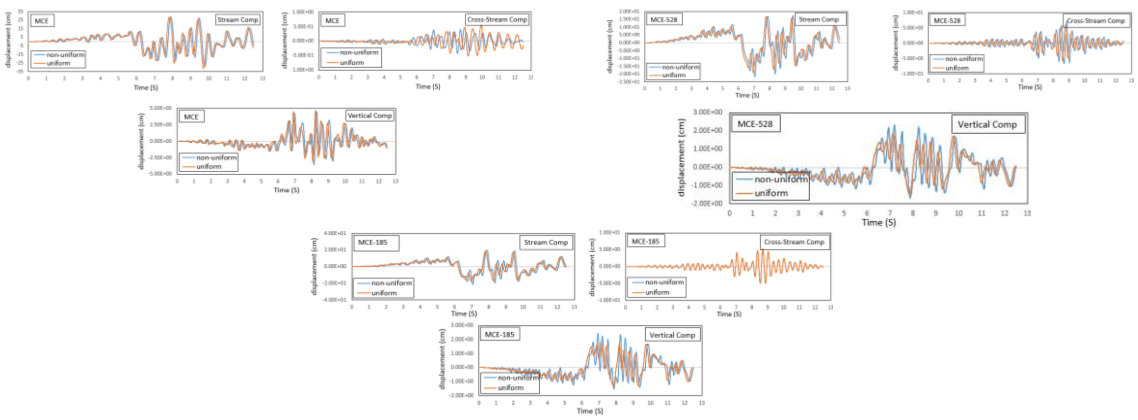


Figure 12: Comparison of the time history of displacement in the stream, cross-stream and vertical direction

Table 6: Maximum displacement values for the crown central axis nodes and the left and right anchors for the Northridge earthquake record

Earthquake elvel		Max Displacement (cm)					
MCE	Node 50						
	Directions	Stream: Towards Down-Stream	Stream: Towards Up-Stream	Cross-Stream		Vertical	
	NON-UNIFORM	-28.8	29.3	-0.42	0.4	-3.56	4.46
	UNIFORM	-30.9	28.7	0.51-	0.55	-3.13	4.63
	Variation (%)	-6.8%	2.1%	-17.6%	-27.3%	13.7%	-3.7%
	Node 528						
	Directions	Stream: Towards Down-Stream	Stream: Towards Up-Stream	Cross-Stream		Vertical	
	NON-UNIFORM	-21.6	17.31	-6.74	7.15	-1.67	2.33
	UNIFORM	-19.1	16.9	-5.8	5.94	-1.5	1.9
	Variation (%)	13.1%	2.4%	16.2%	20.4%	11.3%	22.6
	Node 185						
	Directions	Stream: Towards Down-Stream	Stream: Towards Up-Stream	Cross-Stream		Vertical	
	NON-UNIFORM	-21.3	19.8	-4.98	5.24	-1.5	2.44
	UNIFORM	-17.3	18.8	-4.98	5.24	-1.34	1.8
	Variation (%)	23.12%	5.3%	0	0	11.9%	35.5%

As shown in Figure (12) and Table (6), the number of displacements in the central axis of the crown in uniform stimulation was greater than non-uniform. But in the left and right quadrant, the displacement values in the non-uniform state are greater than the uniform. The rate of decrease in displacement in non-uniform movements compared to uniform movements in the flow direction for the central crown node was 6.8% and the rate of displacement increase in the right nodal quarter was 13.1% and in the left nodal quarter was 23.12%. The maximum displacements in the central crown are in the upstream non-uniform excitation and the downstream uniform mode. In one quarter the right anchor is downstream in both stimulation and the left anchor quarter is a non-uniform downstream position and in a uniform upstream stimulation. In general, it can be said that the maximum displacement of the dam in most of the investigated locations is higher in non-uniform motions than in the Northridge earthquake motions, but the percentage increase is limited to 23%.

12. CONCLUSION

This paper investigates the effects of non-uniform earthquake excitation on linear response of long arch dams. Karun 3 double-arch concrete dam was selected as the study dam. An earthquake recorded at the dam and wake level was used by the Dam Accelerometer Network on 2007.11.20 and the Northridge earthquake for analysis. Records obtained from the dam site were modified without altering their frequency content and were scaled at three seismic hazard levels using a method similar to Regulation 2800 with site spectrum. All three earthquake components were applied to ANSYS11.0 finite element software as non-uniform input for analysis. Station S01 record was used as input for uniform excitation. In the Northridge earthquake, for the non-uniform excitation, the record was applied asymmetrically with a frequency content to the joint boundary of the dam and foundation.

The results of the non-uniform analysis with the real earthquake appear to be significantly different from the non-uniform Northridge earthquake, indicating that the time difference of motion is not the only important factor and the frequency content of the earthquake can be a more effective factor in investigating non-uniform earthquakes. Therefore, it is not useful to investigate non-uniform earthquakes using time-varying earthquakes.

Thus the difference in results can be attributed to the difference in the frequency content of the records recorded at different points of the dam and non-synchronous, for real earthquakes and only non-synchronous for Northridge earthquake. Comparison of the results shows that the non-uniform earthquake motions increase the dam responses. This was observed in the present studies up to a 20% increase in the response of the central crown displacement for the 2007.11.20 earthquake and a 6.8% decrease for the Northridge earthquake. Therefore, to identify the dynamic behavior of the dam and to calculate the responses, uneven stimulation in the safety assessment and design of the high dams should be considered, and further studies using actual records are necessary to more accurately explain the effects.

13. REFERENCES

[1] Zerva, A. Zervas, V. (2002) “Spatial variation of seismic ground motions”, An Overview, Applied Mechanics Reviews. No.3, 55 271-97.
[2] Der Kiureghian, A. (1996) “A coherency model for spatially varying ground motions”, Earthquake Engineering and Structural Dynamics, 25, 99-111.
[3] Proulx, S., Darbre, G. and Kamileris, N. (2006) “A comparison of recorded and computed earthquake motions of large concrete dams”, First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, Paper No.627.
[4] Hall, J., Alves, S.W. (2005), “Non-uniform Ground Motion Effect at Pacoima Dam“, Department of Civil Engineering California Institute of Technology Pasadena, CA.
[5] Alves, S.W., and Hall, J.F. (2006), “Generation of Spatially Non-uniform Ground Motion for nonlinear analysis of a Concrete Arch Dam“, Earthquake Engineering and Structural Dynamics, Vol.35,pp.1339-1357.
[6] Alves, S.W., and Hall, J.F. (2006), “System Identification of a Concrete Arch Dam and Calibration of Its Finite Element Model “, Earthquake Engineering and Structural Dynamics, Vol.35, pp.1321-1337.
[7] Chopra A, Wang J. (2010), “Earthquake Response of Arch Dams to Spatially Varying Ground Motion”, Earthquake Engineering and Structural Dynamics, No.8, 39 887-906.
[8] Ghaemian, M., Sohrabi-Gilani, M. (2012), “Seismic Responses of Arch Dams Due to Non-uniform Ground Motions“, ScientiaIranica, 19(6), 1431-1436.
[9] Sohrabi-Gilani, M., Ghaemian, M. (2012), "Spatial Variation Input Effects on Seismic Response of Arch Dams." ScientiaIranica 19, no. 4: 997-1004.
[10] Tarinejad, R., Fatehi, R., and Harichandran, R.S. (2013), “Response of An Arch Dam to Non-uniform Excitation Generated By a SeismicWave Scattering Model.” Soil Dynamics and Earthquake Engineering, 52, 40-54. doi:10.1016/j. soildyn.2013.04.011.
[11] Akbari, M., Hariri-Ardebili, M.A., Mirzabozorg, H. (2013), “Nonlinear Response of High Arch Dams to Non-uniform Seismic Excitation Considering Joint Effects“, Journal of Engineering.
[12] Akbari, M., Keyhani, A. (2015), “Linear Seismic Response of Arch Dams to Non-uniform Excitations Considering Load Combination Effect“, National Conference on Structural Engineering IRAN.
[13] H. Mirzabozorg ., M.A. Hariri-Ardebili., M. Heshmati., & S.M. Seyed-Kolbadi.(2014). Structural safety evaluation of Karun III Dam and calibration of its finite element model using instrumentation and site observation. ELSEVIER.