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STUDY THE EFFECT OF SOIL BOUNDARY CONDITIONS ON THE BODY STRESSES OF CONCRETE GRAVITY DAMS

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ABSTRACT

The foundation is usually assumed to be massless in seismic analysis of concrete dams. In this study, the dynamic response of the dam was studied by modeling of reservoir and foundation through examining appropriate boundary conditions for the far end of the reservoir and foundation. In this study, four modes were considered according to the foundation conditions and wave conditions, and the critical condition was determined. The reservoir was modeled in a compressible mode by the finite element method with appropriate boundary conditions. The results showed that the foundation mass effect on the seismic response of the dam cannot be neglected. Also, with increased foundation depth, the rate of stresses in different elements of the dam will reduce.

KEYWORDS: CONCRETE DAM, DYNAMIC ANALYSIS, RESERVOIR, FOUNDATION, INTERACTION

INTRODUCTION

One of the main issues to be faced in accurately prediction of the behavior of dams against earthquakes and selecting an appropriate analytical model is the issue of dam interaction with reservoir and foundation. Undoubtedly, the most important and critical part in design of dams is foundation. Large dams are often facing with failure as small dams, but, failure of small dams is more common and there are more statistics and reports in this regard. The highest failure statistics and reports related to the new constructed dams; thus, 33% of them have been destroyed during construction time or in the first year of operation and 61% in the first decade of their life. The main reasons for the destruction of 110 dams recorded by the International Commission on Large Dams can be divided into four groups: Filling of the reservoir, flood, earthquakes and other factors. These events are presented in Table 1 associated with the type of failure or occurred damage. The table clearly shows that the effects of ground water on foundation. i.e., the leakage and upward pressure are the most important factors in damage to the dams. Of the total cases provided, 89 cases have occurred due to reservoir filling, suggesting the case as the most critical state during the dam lifetime [1].

Moeni, 2014 studied and compared the dynamic analysis of interaction of structure and water (dams and reservoirs) in three-dimensional, two-dimensional plane stress and two-dimensional plane strain states [2]. Rastegarfar, 2012 evaluated the stability of Dez adjusting dam and compared analysis methods, including three-dimensional, two-dimensional plane stress and three-dimensional plane strain methods in the Lagrangian and the added mass approaches [3]. Hashemi, 2007 studied the effect of hydrodynamic force exerted on the weight and arch dams subjected to earthquake using a numerical finite element method based on Euler–Lagrange equation and used the ANSYS software for this purpose [4]. Pekau et al., 2000 Using a numerical model, Goangelon made a seismic analysis on concrete gravity dams, and the Koyna dam as a case study [5].

Table 1: Failure and damage of concrete dams built on rock

Total	External reasons			Tank filling	Factors / Events
	Others	Earthquake	Flood		
37	1	2	4	30	SEEPAGE
30	-	-	2	28	High pressure
21	-	1	-	20	Inhomogeneous deformation
15	3	-	2	10	Shear failure foundation and piers bound
7	-	-	6	1	Downstream erosion of the surface flow
110	4	3	14	89	Total

They evaluated the effect of fracture energy parameters with nonlinear fracture mechanics criterion validity in the seismic behavior of concrete dams. To evaluate the crack growth of Koyna dam, Calayir and Karaton, 2005 used the smeared crack model and the fracture energy of 150 Newton per meters to do the analysis. In this study, using a finite element method and ABAQUS software, the dynamic analysis of concrete dam against the earthquake was done considering the interaction of dam with reservoir and foundation [6].

MATERIALS AND METHODS

Rudbar Dam in Lorestan Province was selected as a case study for modeling. Rudbar Dam is a concrete gravity dam that a Roller Compacted Concrete (RCC) has been used at the time of its construction. The dam crest length and width are respectively as 185 and 10 m, with a dam crest elevation of 1774 m. The maximum water level during the flood (100,000 years) is as 1774 at upstream and 1624 at downstream; the minimum water level at upstream is equal to 1700 and 1615 at the downstream, while the normal levels of water in the upstream and downstream are as 1768 and 1615, respectively. The Koyna earthquake accelerograms record was used in dam-foundation analysis and dam-reservoir analysis. The Concrete Damage Plasticity model was used in all models for concrete aggregates. This model is embedded in the ABAQUS / Explicit and ABAQUS / Standard environments for modeling concrete and other quasi-brittle materials in a variety of structures (beams, trusses, shells and solid objects). The plastic behavior of soil was assumed according to modified Drucker - Prager Model. To compare the results in different modes, five areas on the body of the dam were selected, and the stresses of these elements were evaluated during the analysis (**Figure 1**).

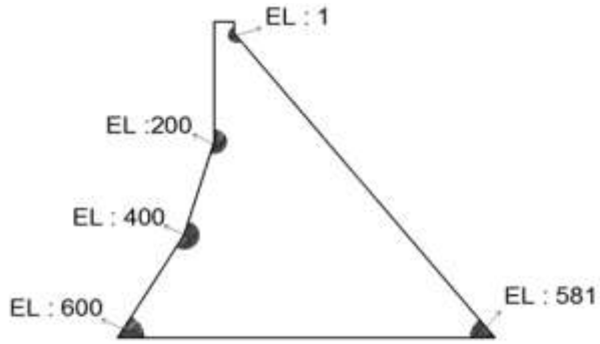

Figure 1: Selected elements in the dam body to evaluate the stress

DISCUSSION

To assess the interaction of dam and foundation, the foundation depth was studied in 10 states of foundation depth to dam height ratio ($\frac{h'}{h}$). Thus, the foundation depth was changed as 1, 2, 3 to 10 times of the height of the dam. To examine and compare the results in different states of analysis, the number of elements in the dam body was considered constant. The 4- node quadrilateral elements were used in the model, in which 700 CPE4R elements were used to model the dam, and AC2D4 element was used to model the soil. Given that the foundation depth is changed, the number of elements was also increased. The results of the interaction of dam and foundation with the empty reservoir are shown in Figure 2. In this analysis, the foundation depth was considered 1 times of the dam height. Given that the maximum stress is used in the designs, the maximum stresses in each element for different states of the foundation depth were drawn by element separation. For example, the plot for element 1 was drawn in Figure 3, and the results of the rest of the elements are listed in Table 2. According to Figure 3, the stresses are declining with increasing the foundation depth in element 1 located at downstream of the dam. This process continues up to 4 times depth, and then, the stresses become almost constant. Given that the tensile stress of the concrete failure is equal to 9.2 MPa, the element 1 located at downstream of the dam will face failure, in analysis, when the foundation depth becomes 4 times of the height of the dam. According to Table 2, it can be concluded that with increasing depth of foundation, the rate of stresses in different elements of the body of the dam would reduce. This occurs because the soil has the ability to withstand stress, and also, a part of the energy generated by the earthquake is amortized by the soil body.

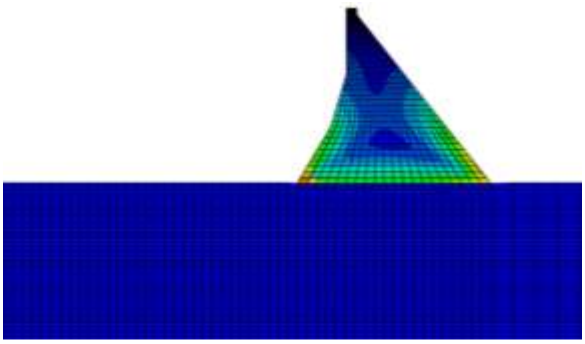

Figure 2: Interaction of dam and foundation; foundation depth equal to the height of the dam

Figure (4) shows the maximum negative stress generated in element 1. Table (3) shows the maximum negative stress generated in the elements of the dam body. According to Figure 4 and Table 3, following increased foundation depth, the amount of negative stresses created in the elements would reduce. Considering that the final yield stress of concrete is13 MPa, these elements would not experience failure. To investigate the interaction of dam and reservoir, the reservoir length was considered as 1, 2... to 10 times of the height of the dam.

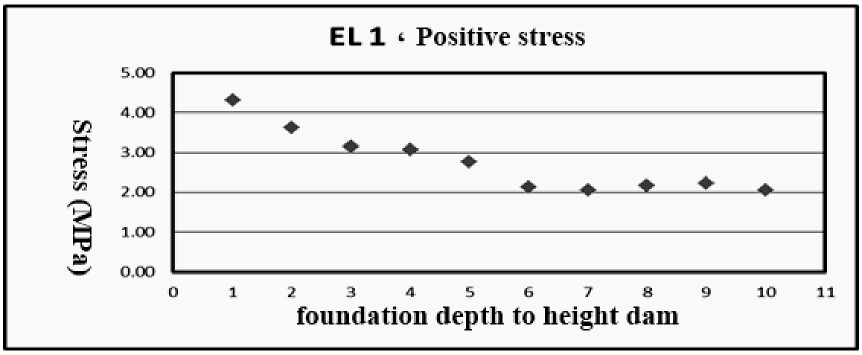

Figure 3: The maximum positive stress in element 1 in different cases of the foundation depth

Table 2: The maximum positive stress (MPa) of elements in the dam body in case of dam – foundation

Element / $\frac{h'}{h}$	**EL 1**	**EL 200**	**EL 400**	**EL 600**	**EL 581**
1	4.32	3.15	3.62	6.20	14.6
2	3.62	3.05	3.15	5.62	14.8
3	3.15	3.15	3.16	4.32	11.5
4	3.06	3.06	2.93	3.62	9.88
5	2.76	2.76	2.84	3.60	7.20
6	2.13	2.13	2.05	3.15	5.85
7	2.06	2.06	2.05	3.37	5.39
8	2.17	2.17	2.05	3.39	5.39
9	2.23	2.23	2.05	3.15	5.44
10	2.05	2.05	2.05	3.15	3.62

To achieve accurate results, the number of elements of the dam body was considered constant in all models. According to Figure 5, with increasing the reservoir length in element 1 located at downstream of the dam, the stresses are rising as well. This trend continues up to the 3 times length, and then, the stresses become almost constant.

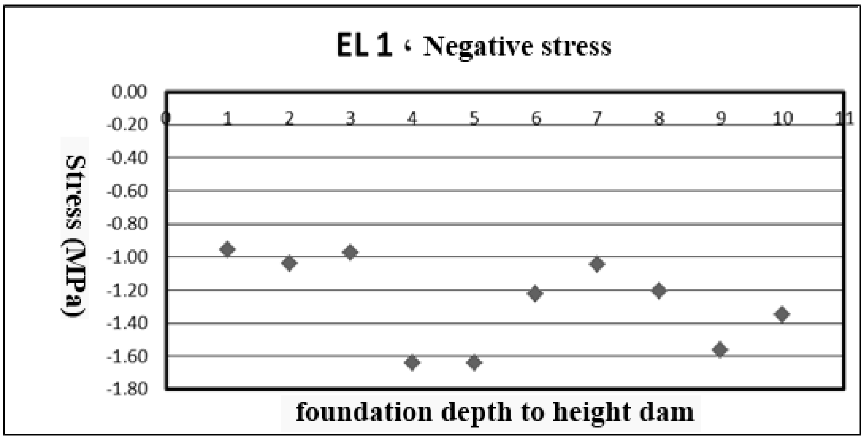

Figure 4: The maximum negative stress in element 1 in different cases of the foundation depth

Table 3: The maximum negative stress (MPa) in elements of the dam body in case of dam – foundation

Element $\frac{h'}{h}$	EL 1	EL 200	EL 400	EL 600	EL 581
1	-0.95	-0.97	-1.04	-1.95	-3.06
2	-1.04	-0.97	-0.97	-1.04	-3.04
3	-0.97	-0.97	-1.64	-0.95	-1.71
4	-1.64	-1.64	-1.22	-1.04	-2.26
5	-1.64	-1.64	-1.35	-0.94	-1.95
6	-1.22	-1.22	-1.35	-0.97	-1.49
7	-1.05	-1.05	-1.35	-1.26	-1.73
8	-1.21	-1.21	-1.35	-1.11	-1.73
9	-1.56	-1.56	-1.35	-0.97	-0.51
10	-1.35	-1.35	-1.35	-0.97	-1.04

Table (4) shows the maximum positive stress generated in the elements of the dam body. By increasing the reservoir length, the rate of positive stress created in these elements will also increase. Given that the tensile stress of the concrete failure is equal to 9.2 MPa, the results indicate that the elements 1, 200, 400 and 600 will experience failure, but the element 581 does not crack. Table (5) shows the maximum negative stresses generated in the elements of the dam body. According to Table (5), negative stresses are rising with increase in the reservoir length in the element 1 located at the dam downstream. This trend continues until the 3 times length, and after that, the stresses become almost constant. By increasing the reservoir length, the negative stresses created in these elements would increase. Given that the ultimate yield stress of concrete is equal to 13 MPa, these elements do not face failure, and only the only element 581 located at the dam toe faces failure and cracking.

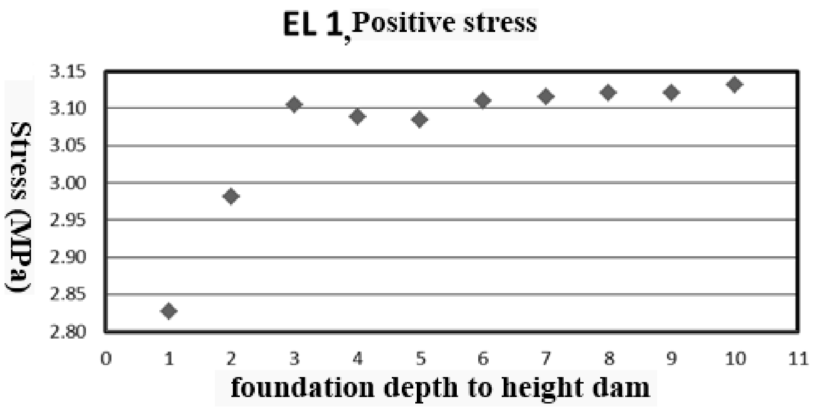

Figure 5: The maximum positive stress in element 1 in different cases of the reservoir length

Table 4: The maximum positive stress (MPa) of elements in the dam body in case of dam-reservoir

Element $\frac{h'}{h}$	EL 1	EL 200	EL 400	EL 600	EL 581
1	2.83	2.82	3.36	2.17	0.56
2	2.98	3.47	5.41	3.25	1.05
3	3.10	4.34	5.97	4.33	1.09
4	3.09	4.77	5.86	4.54	1.07
5	3.08	3.03	4.85	3.03	0.92
6	3.11	4.98	5.82	4.55	1.04
7	3.12	5.20	5.97	4.58	1.04
8	3.12	5.20	5.97	4.55	1.04
9	3.12	5.20	5.97	4.55	1.04
10	3.13	5.20	6.34	4.55	1.03

According to the results of the analyses of dam-reservoir and the dam-foundation, in dynamic analysis for modeling of dam-reservoir-foundation, the reservoir length can be considered 3 times of the dam height. Also, the foundation depth can be considered 4 times of the height of the dam. Next, the dam response was studied in dynamic analysis associated with dam and the reservoir. An Accelerogram was used to load the dam. To evaluate the responses, two fine and coarse meshing were considered. In the network with fine mesh, the 4-node quadrilateral elements were used, in which 700 CPE4R elements were used to model the dam, and 14,000 CPE4R type elements were used to model the soil. Also, 1500 elements, AC2D4 type, were used for reservoir modeling. In the coarse mesh network, the 4 nodes quadrilateral elements were used, in which 350 elements of type CPE4R were used to model the dam, while 10500 CPE4R elements were used for soil modeling. Also, 900 AC2D4 elements were considered for modeling the reservoir.

Table 5: The maximum negative stress (MPa) in the elements of the dam body in the case of reservoir – dam

Element $\frac{h'}{h}$	EL 1	EL 200	EL 400	EL 600	EL 581
1	-4.95	-0.94	-2.77	-2.54	-13.6
2	-5.22	-1.15	-4.46	-3.82	-24.5
3	-5.44	-1.44	-4.92	-5.10	-25.6
4	-5.41	-1.59	-4.83	-5.36	-25.2
5	-5.40	-1.01	-4.00	-3.57	-21.8
6	-5.45	-1.66	-4.80	-5.35	-24.5
7	-5.46	-1.73	-4.92	-5.37	-24.5
8	-5.46	-1.73	-4.92	-5.34	-24.5
9	-5.47	-1.73	-4.92	-5.34	-24.5
10	-5.48	-1.73	-5.23	-5.34	-24.3

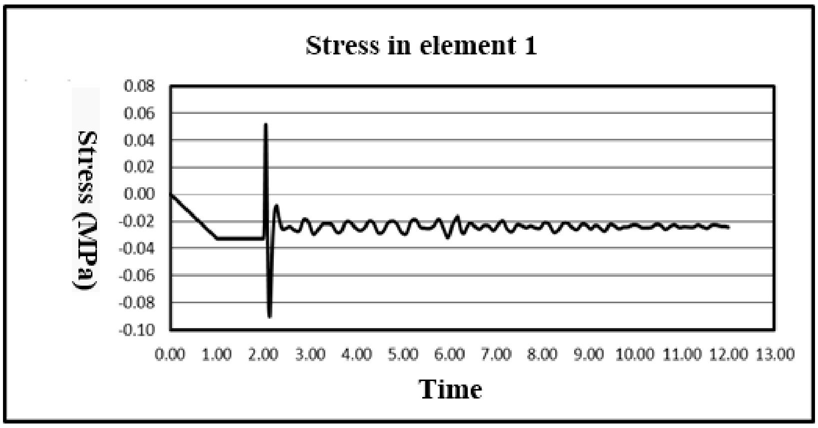

Figure 6: Stress in element 1, dam-reservoir-foundation interaction, Slaton Sea earthquake

Figure (6) shows the stresses in element 1 caused by the Slaton Sea earthquake. The magnitude of this earthquake is 12.0 g. The maximum stress occurred due to impact of this earthquake is close to 0. 06 MPa; considering the value of tensile stress of the concrete failure, this element does not crack. Figure 7 shows the effect of meshing on the dam response. According to Figure 8 showing the fine and coarse meshes, the mesh size has little effect on the response of the dam. However, in meshing of dam, reservoir and foundation, in both cases of fine and coarse meshes, the ratio of mesh size was not more than 10.

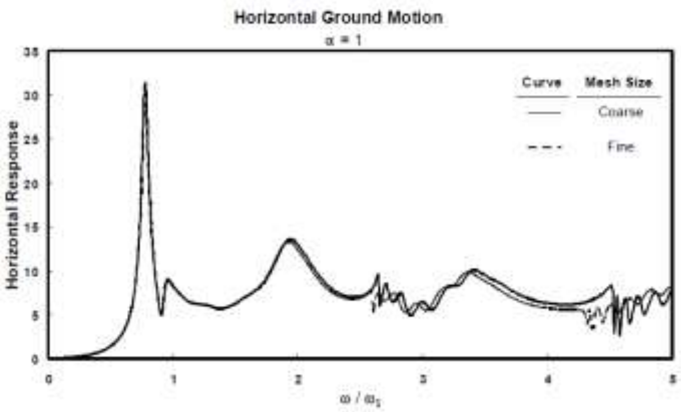

Figure 7: The effect of fine meshing on the response of the dam crest

CONCLUSION

In this study, the dynamic response of the dam was investigated by reservoir and foundation modeling and through evaluation of appropriate boundary conditions for the far end of the foundation and the reservoir. According to the results of the dynamic analysis of dam-foundation system, the foundation depth can be considered 4 times of the dam height for modeling, and there would be no need for further modeling. The depth more than 4 times the dam height only increases the computing time and also takes additional memory of the computer. Also in dynamic analysis of dam-reservoir system, the reservoir length can be considered as 3 times of the height of the dam for modeling, and there would be no need for further modeling. This issue arises because the wave generated in the fluid is released along the reservoir and causes the distancing of the force influencing the dam body. If the length to width ratio of the used elements does not exceed 10, the size of meshes will have little impact on the dam response.

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