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Earthquake Behaviour of Concrete Gravity Dams Considering Various Interaction Conditions

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Abstract:

In this study, Boyabat dam, which is concrete gravity (CG) dam, located a highly seismic zone in Turkey was selected for numerical analyses and it was numerically modelled considering empty and full reservoir water conditions by finite element method. Seismic response of the selected CG dam was examined considering seven different dam–foundation interaction conditions. Each interaction conditions have different mechanical properties and different friction properties. In total, 14 different seismic analyses were performed to understand the effect of different interaction conditions on behaviour of the dam for various reservoir conditions. Two-dimensional fluid finite elements based on the Lagrangian approach was used to model the hydrodynamic pressure of the reservoir water. The acceleration records of 1999 Düzce earthquake (Mw 7.1) were used in all seismic analysis. According to the numerical solutions, the change of horizontal displacements (upstream-downstream direction) was evaluated for two-dimensional dam–reservoir–foundation interaction systems. It is clearly seen in this study that when the different interaction conditions are used between interaction surfaces of the dam, two dimensional linear behaviour of the concrete gravity dam clearly changes. According to the two dimensional linear analyses, as the friction between dam and foundation increases, the relative deformations decreased while the total deformations increased.

Key words: Friction, Concrete gravity dam, Dam–reservoir–foundation interaction, Lagrangian approach.

1. Introduction

Basically, concrete gravity dams are solid concrete structures that maintain their stability against design loads from the geometric shape and the mass and strength of the concrete. Generally, although they are constructed on a straight axis, they may be slightly curved or angled to accommodate the specific site conditions. Gravity dams typically a consist of no overflow section(s) and an overflow section or spillway. The earthquake loadings used in the design of CG dams are based on design earthquakes and site-specific motions determined from seismological evaluation. Besides seismological evaluation should be performed on all projects located in seismic zones 2, 3, and 4 (USACE 1995). The seismic safety of concrete gravity dams is extremely vital due to Turkey is located on the strong seismic zone.
Behaviour of the concrete gravity dams under seismic loading was investigated by many investigators (Wang et al. 2017, Yazdani and Alembagheri 2017). Westergaard (1933) suggested very important information about the dam-foundation-reservoir interaction under seismic loads in 1933. In addition, Westergaard examined that the importance of estimating the hydrodynamic pressure on rigid dams during earthquakes. In the later years, the effect of water compressibility

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on the hydrodynamic pressure, acting on a dam body, were examined for vertical-horizontal ground motions (Chopra 1966). The improvements in 2D analysis took place in the literature in the last decade of the 20th century (Fenves and Chopra 1984). 2D finite element method (FEM) is an effective method and it was used for evaluating CG dams in earthquake zones by many investigators. Fok and Chopra (1985) studied flexibility of the foundation of considering those finite elements to be massless. Hall (1988) summarizes the results of the dynamic and seismic behaviour of concrete dams, in terms of experimental behaviour and observational evidence. Studies also show that the dynamic response of concrete dams can be defined by implementation of 2D finite element modelling (Akköse and Şimşek 2010, Zhang and Wang 2013). Fanelli (1992) modelled the dynamic behaviour of the Talvacchia dam in Italy under earthquake records. Lei (2010) examined the role of the Zipingpu reservoir in triggering M=8 Wenchuan earthquake. Chen and DU (2011) are investigated elasto-plastic dynamic analysis of a high roller-compacted concrete gravity dam with a complex foundation was conducted and the dynamic strength reduction method was employed to analyse the anti-sliding stability of the dam foundation under dynamic loads. Kartal (2012) investigated three-dimensional earthquake analysis of roller-compacted concrete dams to observe behaviour of RCC dam. Several studies have contributed to linear methodologies in previous studies (Maeso et al. 2002, Alves et al. 2006, Chopra and Wang 2010). Mridha and Maity (2014) investigated concentrates on evaluation dynamic response of concrete gravity dam-reservoir system by experimental and numerical analysis. The stresses at various points and path of propagation of tensile damages were computed and numerical results were compared with the experimental results.

This study aims to fill the lack of the studies related to the seismic response of concrete gravity dams considering dam-foundation interaction. The behaviour of CG dams has not been investigated in the literature for totally 7 various interactions conditions. It is clearly seen in this study that how seismic behaviour of the dam changed when interaction condition was altered. Due to this result, this study is different from other ones. We selected the Boyabat Concrete Gravity Dam in Turkey which is located in the Sinop for numerical analyses. Two-dimensional dam-reservoir-foundation interaction system of dam was modelled using ANSYS software which is based on the finite element method in order to understand the effect of various interaction conditions on the seismic behaviour of the dam. The reservoir length of the CG dam was considered as three times of the dam height because of it is the most effective reservoir length (Kartal et al. 2017). In addition, downstream side and foundation side were extended as the height of the dam while modelling Boyabat dam. The 2D fluid finite element based on the Lagrangian approach was utilized to obtain the hydrodynamic pressure effect of the reservoir water. Seven different interaction cases were used for the dam-foundation interaction and empty-full reservoir conditions were considered for the seismic analyses. Fixed boundary conditions were considered for boundary of the two dimensional finite element model. Then linear time-history analyses were carried out to obtain the earthquake response of the dam. According to the numerical analyses, horizontal displacements (upstream-downstream direction) were evaluated for different interaction conditions. The numerical results clearly show that horizontal displacements which occurred for the full reservoir water condition of the dam is greater than the empty reservoir water condition of the dam. When interaction conditions change, the structural response of concrete gravity dam clearly changes. Too close horizontal displacement values were observed for bonded case, case with interface elements, coupled case and case with welded contact in the numerical analyses.

3. Boyabat Concrete Gravity Dam

3.1. General Information

General State Hydraulic Works (DSI) which is responsible for planning and implementation of water resources development projects in Turkey, in total 204 large dams and 339 moderate dams were constructed so far. Beside those completed projects, 111 large dams and 159 moderate dams are also under construction. The Boyabat Dam is concrete gravity dam and it is located in the north of Turkey, about 123 km further from the Black Sea border, on the Kızılırmak River, 10 km southwest of the Durağan district centre. The project area is surrounded by the Ilgaz Mountains, reaching 1500-1600 m elevations in the north and west (Fig. 1). It is also surrounded by Kunduz and Çal Mountains in the south and Altinkaya Dam Reservoir in its downstream. The dam site is 120 km west of the province of Samsun and 80 km south of Sinop province. The Boyabat dam was constructed in 48 months and energy production was started on 5 November 2012. Height of Boyabat dam height is 195 m and maximum water level is 190 m. Elevation of dam crest is 335.00 m. Dam body volume is 2300000 m³. The total lake volume is 3.557 km³. In addition, drainage area is 64724 km². There is 6 spillway covers in the dam. The spillway capacity is 9300 m³/s (DSI 2018).

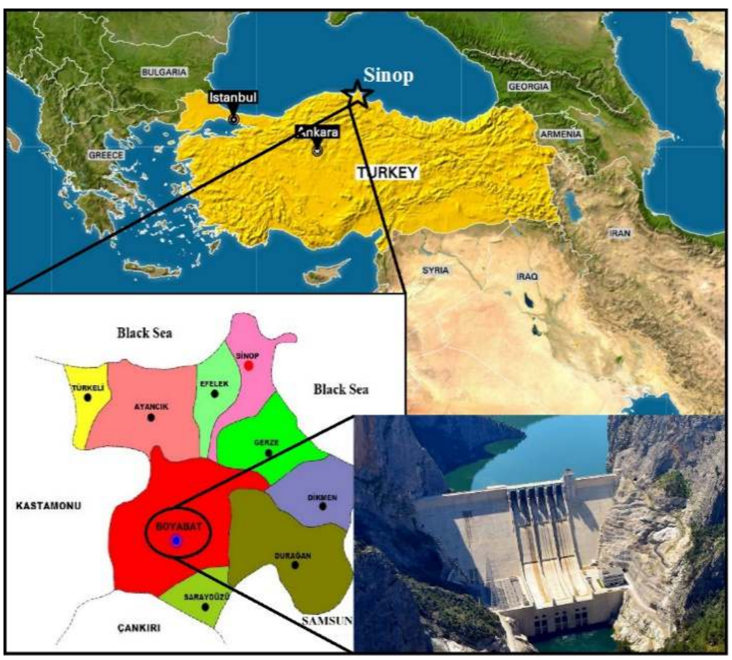

Fig. 1. Boyabat dam and its location.

3.2. Finite Element Model and Material Properties of Boyabat Dam

We used ANSYS finite element analysis software for numerical analyses because of it enables us to perform linear dynamic analysis by using finite element method (Moaveni 1999). In addition, we refer the height of the dam as “h” and the foundation was extended as same rate in the transverse river, downstream and gravity directions in 2D modelling. The reservoir length was also extended as three times of dam height and implemented in numerical analysis, given in Fig. 2. We utilized PLANE42 for 2D modelling of solid structures; here, the element can be represented either as a plane or as an axisymmetric, is defined by four nodes having two degrees of freedom at each node (x and y directions). We also used FLUID79, which is the modification of structural solid element PLANE42, to model fluids contained with vessels having no net flow rate. While the two-dimensional finite element model of Boyabat dam was modelling, totally 700 finite elements were used for the empty condition of dam. 200 finite elements are also used for dam-body and 500 elements are used for foundation. In addition, totally 1300 finite elements were used for full reservoir condition of CG dam. 600, 500, 200 finite elements are used for reservoir water, foundation and dam-body, respectively. The dimensions of each finite element are very close together (Kartal et al. 2017). While defining the contact-target couples, the mechanical properties of each were separately defined in the program. Fluid and solid element matrices were computed using the Gauss numerical integration technique (Wilson and Khalvati 1983). The two-dimensional finite element model of Boyabat dam includes foundation, dam body and reservoir water. The material properties of Boyabat CG dam body and foundation are given in Table 1.

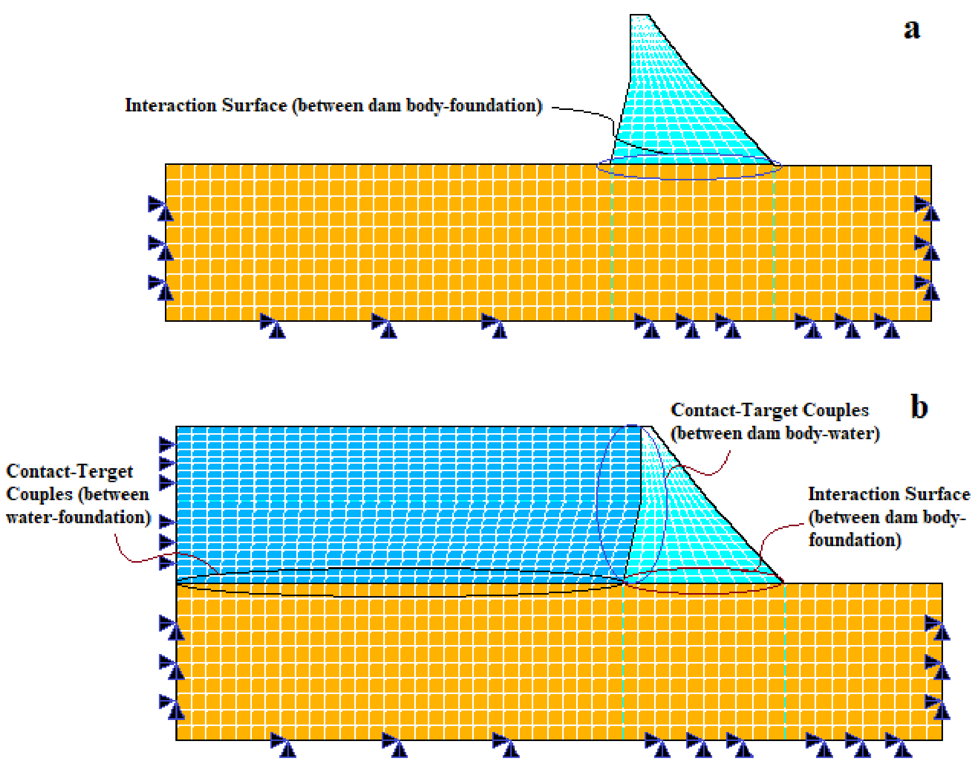

Fig. 2. a) 2D empty FEM of Boyabat Dam using in numerical analyses, b) 2D full FEM of Boyabat Dam using in numerical analyses.

Table 1 Material properties used in numerical analysis (DSI 2018).

	Modulus of Elasticity (GPa)	Poisson's Ratio	Mass Density (kg/m³)
Concrete (Dam)	30	0.20	2530
Rock (Foundation)	25	0.18	2800

Due to the magnitude and Düzce earthquake which the largest natural disasters of the 20th century in Turkey, are utilized in this study. The 27.76 sec time history accelerogram analyses were utilized in dynamic response analysis (Fig. 3). The time interval was chosen as 0.01 sec in the linear time history analyses which involve Newmark algorithm (Newmark 1965). The first six vibration frequencies were considered to calculate Rayleigh damping constants.

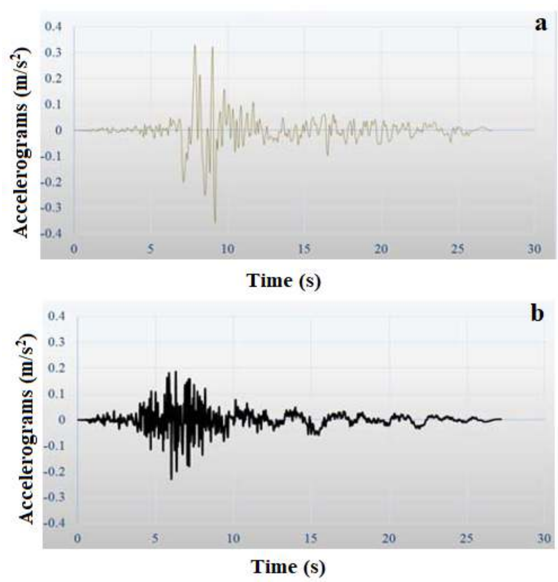

Fig. 3. a) North-south component of accelerogram, b) East-west component of accelerogram; Mw 7.1 1999 Düzce Earthquake in Turkey.

4. Numerical Evaluations and Results

When considered interaction between the two discrete surfaces, it is possible to obtain more realistic numerical results by defining interaction couples between these surfaces. For this purpose, the two-dimensional finite element model of the Boyabat dam was modelled and different interaction elements were considered between discrete surfaces (between dam body and foundation). We examined that how seismic behaviour of the CG dam changes when various interaction elements are used between dam and foundation. In total, 2 different two-dimensional finite element models were created for numerical analyses. One of these models is adjacent model and it is named as welded and other is discrete finite element model. Four different contact-target couples were used between the discrete surfaces. The contact-target couples were defined between the dam-foundation, foundation-reservoir and reservoir-dam, respectively. Besides interface elements are considered between dam and foundation rock. The mechanical properties and application processes of these interaction elements are different from contact elements. Finally, coupling proves is applied between adjacent joint of dam and foundation. In this process, adjacent horizontal and vertical displacements of nodal points dam and foundation are equalled. Numerical analyses were separately performed for 14 different cases. According to numerical analyses, the horizontal deformations in negative and positive directions were obtained for each case, respectively. In addition, each result was showed graphically in detail and all results were compared with to each other. 14 different cases were presented for both conditions of the dam in Table 2.

Table 2 Dam-foundation interaction conditions considered in numerical analysis

Case	Reservoir	Interaction Element	Statement
Case 1		Bonded	
Case 2		Rough	2 - 3 Noded Contact-Target Elements
Case 3		No Separation	
Case 4	Empty	Standard	
Case 5		Interface	4 Noded Interface Element
Case 6		Coupling	2 Noded Couple Element
Case 7		Welded	None (Uses the same nodes)
Case 8		Bonded	
Case 9		Rough	2 - 3 Noded Contact-Target Elements
Case 10		No Separation	
Case 11	Full	Standard	
Case 12		Interface	4 Noded Interface Element
Case 13		Coupling	2 Noded Couple Element
Case 14		Welded	None (Uses the same nodes)

4.1. Horizontal displacements in downstream direction

In this section, 14 different numerical analysis results were shown in detail for the empty and full reservoir condition of the CG dam (Fig. 4-5) in detail. When the horizontal displacements in the downstream direction along the dam body were examined, it is clearly seen that the horizontal displacements for full reservoir condition are bigger than those of empty condition. For the empty reservoir condition of the CG dam, numerical analyses clearly showed that the largest horizontal displacements occurred in Case 1. The closer horizontal displacements occurred in Case 4 and Case 7. When Case 5 is compared with Case 1,6,7, the similar horizontal displacement diagram was observed, but relatively smaller horizontal displacements took place in Case 5. In addition, the similar horizontal displacement curve took place in the positive direction along the dam body for Case 1,5,6,7. For Case 2,3,4, although the close horizontal displacement curve was obtained along the dam body, small horizontal displacements were observed along the dam body for these cases. (Fig 4). For full reservoir condition of the CG dam, too close horizontal displacements values were observed in Case 12 and Case 14 just like the empty condition of the dam. Moreover, when Case 13 compared with Case 8, smaller horizontal displacement values took place in Case 13 (Fig. 5). In general, the largest displacements occurred in Case 1 and Case 8 for empty and full reservoir conditions at the dam crest. These displacement values are 3 cm and 3.82 cm, respectively. Besides, the smallest horizontal displacement in positive direction was observed in Case 3 and Case 10 for empty and full reservoir conditions, respectively.

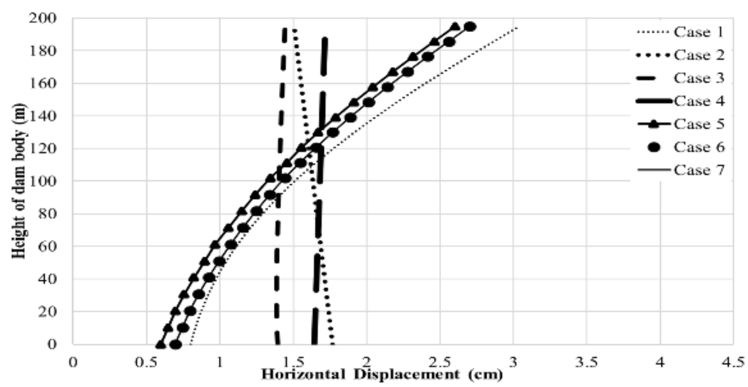

Fig. 4. Horizontal displacement for empty condition in downstream side.

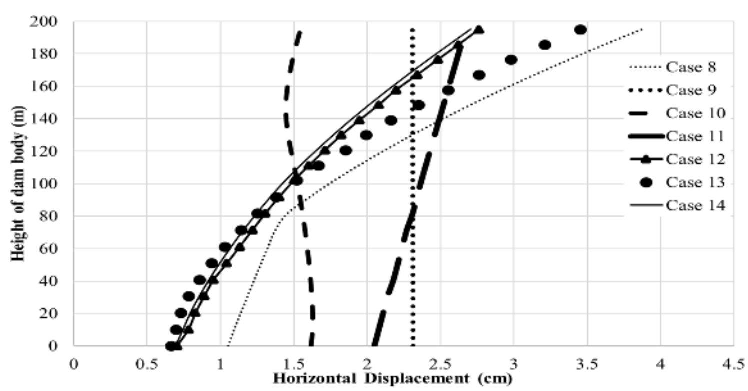

Fig. 5. Horizontal displacement for full reservoir condition in downstream side.

4.2 Horizontal displacements in upstream direction

The horizontal displacements in the upstream direction under seismic effects were examined in this section. Generally, the maximum horizontal displacements for full reservoir condition of the dam are visibly larger than the empty condition of the dam (Fig 6-7). For the empty condition, the maximum horizontal displacement was observed in Case 3 in upstream direction. Very close horizontal displacement values took place for Cases 6 and Case 7 in numerical analyses. When Case 5 was compared with the Case 1,6,7, in despite of smaller horizontal displacements values were observed in Case 5, the horizontal displacement curve of Case 5 is very similar to the Case 1,6,7. In addition, we can clearly see that there are no large displacement differences along the dam body for empty condition of the dam in Case 2 and Case 4 (Fig. 6). When the full reservoir condition of the dam is investigated, it is obviously seen that the maximum horizontal displacement at the crest point of the CG dam is too close for Case 8, 12, 13, 14. In addition, the horizontal displacement differences increase at the bottom elevations of the dam body for these cases (Fig. 7). According to seismic analyses, the maximum horizontal displacement value in upstream direction for empty and full reservoir condition is approximately 4.25 cm and 3.35 cm, respectively.

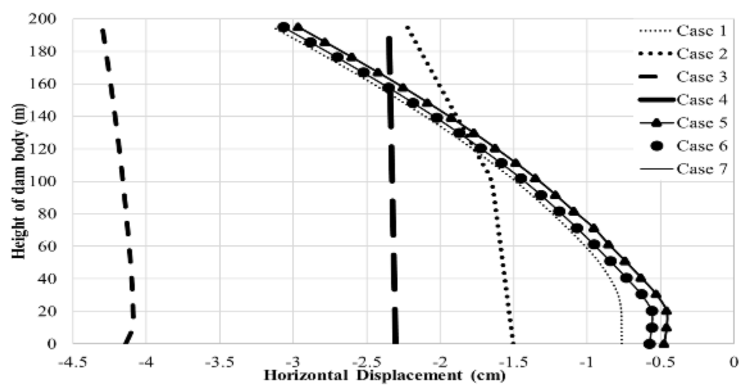

Fig. 6 Horizontal displacement for empty condition in upstream side.

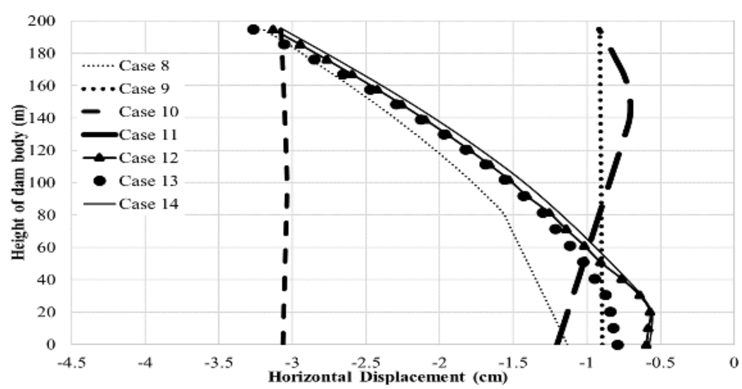

Fig. 7 Horizontal displacement for full reservoir condition in upstream side.

Conclusion

Because of there is not such a comprehensive study in the literature, we think that this study will contribute to the elimination of this deficiency. The investigation of the seismic response of Boyabat CG dam under strong ground motion considering various interaction conditions has led to significant outcomes regarding modelling. In order to understand to what kind of interaction elements can be used between the different surfaces in the finite element model under the effect of the strong earthquake, we modelled 14 different 2D finite element models (discrete and adjacent finite element models). According to numerical solutions, horizontal displacements were examined for each linear analyses. This study represents seismic behaviour of CG dam using various interaction elements taking into account the foundation-dam-reservoir interaction. Our results led to the following conclusions:

• In general, horizontal displacements (upstream side) for full reservoir condition of the dam are clearly bigger than those of empty condition of the dam. In addition, the numerical analyses clearly indicate that the effect of the hydrodynamic pressure of the reservoir water on the CG dams and it cannot be neglected.

• According to the numerical analyses, when the different interaction conditions are defined between the discrete surfaces interacting with each other, the behaviour of the CG dam and horizontal displacements have changed greatly. Very close horizontal displacement values were observed in empty and full reservoir water conditions for bonded contact, joint with interface elements, joint with coupled nodes and welded contact. Different horizontal displacements were observed for other interaction conditions in numerical analyses.

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