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Three Dimensional Nonlinear Seismic Effects of Epicenter Distance of Earthquake on Principal Stress Behaviour of Concrete Gravity Dams

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ABSTRACT

In this study, it is purposed to investigate 3D nonlinear seismic behaviors of concrete gravity (CG) dams considering various epicenter distances. For this aim, Boyabat CG dam that is one of the biggest concrete gravity dams in Turkey is selected as a numerical application. FLAC3D software based on finite difference method is used for modelling and analyzing of the dam. Drucker-Prager nonlinear material model is used for the concrete body and Mohr-Coulomb nonlinear material model is taken into account for the foundation. Free-field and quiet non-reflecting boundary conditions are utilized for the main surfaces of 3D model. Total 5 various epicenter distances of 1989 Loma Prieta earthquake are considered in 3D earthquake analyses and these distances are 5 km, 11 km, 24 km, 85 km and 93 km, respectively. According to 3D seismic results, principal stresses failures of the dam are evaluated in detail. It is clearly seen from this study that the nonlinear seismic behaviors of the CG dams change depending to epicenter distance of the earthquake.

Introduction

Recently, three dimensional (3D) nonlinear analyzing has obviously become widespread in the civil engineering and this practice has been widely used to assess the earthquake performance of concrete gravity (CG) dams (Wang et al. 2017). Nonlinear earthquake behaviors of CG dams under strong seismic loads was investigated by many investigators in the past (e.g. Wang et al. 2017, Yazdani and Alembagheri 2017). Firstly,

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Westergaard has been pioneered to the literature about the seismic modelling and analysis of CG dams. It was suggested very important information about the dam-foundation-reservoir interaction under seismic loads in 1933. In addition, it was examined the importance of the hydrodynamic pressure on rigid dams during earthquakes (Westergaard 1933). In the later years, the effects of water compressibility on the hydrodynamic pressure were examined considering vertical-horizontal ground motions (Chopra 1966). Moreover, the improvements in two dimensional analysis took place in the last decade of the 20th century (Fenves 1984). Then, Fok and Chopra studied seismic flexibility of the dam's foundation considering finite element method (Fok and Chopra 1985). Hall summarized the results of the dynamic and seismic behaviour of concrete dams taking into account experimental behaviour and monitoring evidence (Hall 1988). Besides, Fanelli et al. (1992) modelled the dynamic behaviour of a concrete dam under strong ground motions. Lei (2010) examined the seismic role of reservoir water considering M=8 Wenchuan earthquake. Chen and DU (2011) investigated elasto-plastic dynamic analysis of a high concrete gravity dam. The dynamic strength reduction method was employed to analyze the anti-sliding stability of the dam under dynamic loads. In addition, many studies also showed that the dynamic response of concrete dams can be examined by implementation of 2D finite element modelling (Akköse and Şimşek 2010, Zhang and Wang 2013). In 2019, seismic performance and failure mode of the Jin'anqiao concrete gravity dam based on incremental dynamic analysis was performed. It was concluded in that study that under ground motion loadings of the Jin'anqiao dam, the locations at which functional failure may occur are mostly found in the stress concentration of the dam slope, the boundary of the rolling section, the junction between the dam and dam foundation, and the top of the corridor (Chen et al. 2019). Then, the nonlinear dynamic analysis of Koyna dam was performed using the concrete model with isotropic damage in local approach. Severe damage was found in the form of horizontal cracking observed on both the upstream face of the upper part of dam monoliths (Oudni and Bouafia 2015). Then, it was presented the effects of geometrical dimensions of concrete gravity dams on the seismic response considering different base width/dam height (L/H) ratios. Finite element models of the dam were constituted including five different L/H ratios such as 0.25, 0.5, 0.75, 1.00, 1.25. The results showed that the L/H ratios considerably affect the seismic response of gravity dams (Sevim 2018).

As seen these studies, many investigators were examined the seismic behaviour of CG dams. However, the effects of epicenter distance of earthquake on the seismic behaviour of CG dams were not observed in the literature. Thus, this study supports many important information to the literature about effects of earthquake's epicenter distance on the nonlinear seismic behaviors of these dams. In this study, Boyabat CG dam has 195 m height is selected for 3D seismic analyses. Dam is modelled using FLAC3D software based on the finite difference method. Drucker-Prager and Mohr-Coulomb nonlinear material models are utilized for concrete body and foundation, respectively. Special interface elements are defined to the discrete surfaces (dam body-foundation). Free field and quiet non-reflecting boundary conditions are used for the main surfaces of 3D model. Earthquake analyses are performed for the full reservoir condition of the dam. Total 5 various epicenter distances of 1989 Loma Prieta earthquake are considered in the nonlinear earthquake analyses. Distances of these ground motions to the center are 5 km, 11 km, 24 km, 85 km and 93 km, respectively. Main aim of this study is to assess

the effects of these distances on 3D nonlinear earthquake behaviour of Boyabat CG dam. According to analysis results, principal stresses failures of five different nodal points selected on the dam body are evaluated in detail and these results are compared with each other. In this study, it is clearly seen that epicenter distance of earthquake has very critical seismic effects on the 3D earthquake behaviour of CG dams. When this distance increases or diminishes, earthquake behaviour of the dam clearly changes.

Boyabat Concrete Gravity Dam

State Hydraulic Works (DSI) is very important institution in Turkey and it is responsible for planning and implementation of water resources development projects in Turkey. Total 204 large dams and 339 moderate dams were constructed by DSI. Besides to those completed projects, 111 large dams and 159 moderate dams are also under construction. The Boyabat Dam was constructed as a concrete gravity dam by DSI 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 center. 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 completed in 48 months and energy production was started on 5 November 2012. Boyabat dam's 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.

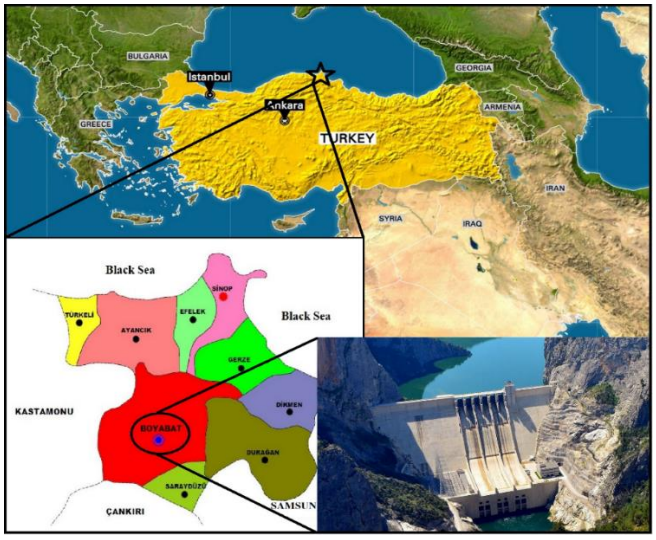

Fig. 1 Location and general view of Boyabat dam

The total lake volume is 3557000000 m3. In addition, drainage area is 64724 km2. There is 6 spillway cover in the dam. The spillway capacity is 9300 m3/s. Material properties of Boyabat concrete gravity dam is shown in Table 1 in detail. According to Table 1, modulus of elasticity of concrete dam body is 30 GPa and this numerical value is 25 GPa for the foundation. Moreover, poisson's ratio of concrete body is 0.20 and it is 0.18 for the foundation. Finally, mass density is 2530 kg/m^3 and 2800 kg/m^3 for concrete body

and foundation, respectively. These material properties are obtained from the original dam project and these parameters are defined to 3D finite difference model of the dam using special fish functions.

Table 1 Material properties of Boyabat CG dam

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

3D modelling and calibrating of Boyabat concrete gravity dam

3D modelling and investigating of the seismic behaviors of concrete gravity (CG) dams such as Boyabat CG dam is vital importance to evaluate the future and safety of such dams. In this section, important information about the modelling of Boyabat dam are explained in detail. Because of Boyabat dam is one of the biggest water structures in Turkey, examining and modelling seismicity of this dam provides significant contributions to the literature. Firstly, the foundation of 3D finite difference model is modelled taking into account the geological structure of the canyon. While modelling the foundation, the height of the foundation is considered as the height of the dam body. Moreover, the foundation is extended towards the dam body's right and left directions as the height of the dam body.

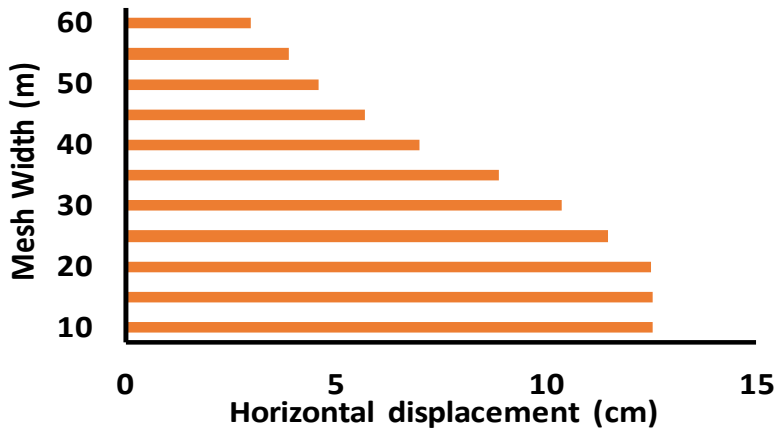

Fig. 2 Horizontal displacement changes on the crest for different mesh widths

While creating the geometry of the dam body, 3D model of all materials is modelled in accordance with the original dam project. In addition, the height of the dam body is modelled in accordance with the elevation of the rough terrain. Totally, there are 2651998 nodal points in the 3D model of Boyabat Dam. Mesh ranges are not randomly created in the 3D model. The most stable mesh range is taken into account in this study as seen in Fig. 2. In order to find correct mesh width, total of 11 different mesh widths were created and seismic analyses were performed for various mesh width. These widths are 10 m, 15 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m, 50 m, 55 m, and 60 m, respectively. It is seen

from numerical analyses that the maximum horizontal displacements on the crest of the dam do not change for less mesh width than 20 m (Fig. 2). Thus, mesh width is selected approximately 20 m for seismic analyses. Moreover, in this study, special interface elements are used between the dam body and foundation to represent the interaction condition of discrete surfaces. Normal (k_n) and shear (k_s) interaction stiffness values are different for each interface surface. Unit of the kn and ks stiffness is stress/displacement (Itasca 2002). In this study, k_n and k_s stiffness are separately calculated for each discrete surface. These stiffness values are considered as approximately 10^8 Pa/m between the dam body and foundation. Shear and normal stiffness values are defined to FLAC3D software using special fish functions. The reservoir water is modelled considering the hydrostatic pressure and leakage in the dam body taking into account the maximum water height (195 m). Free field and quiet (viscous) boundary conditions are applied only lateral surfaces of the 3D model. Firstly, free field special seismic boundary condition is defined to software using special fish functions. Afterwards, the quiet boundary condition is considered to lateral surfaces of the 3D model. These special seismic boundary conditions are shown in Fig. 3. Total 5 various ground motions are used in this study. These earthquakes are practiced to the main surface of the dam.

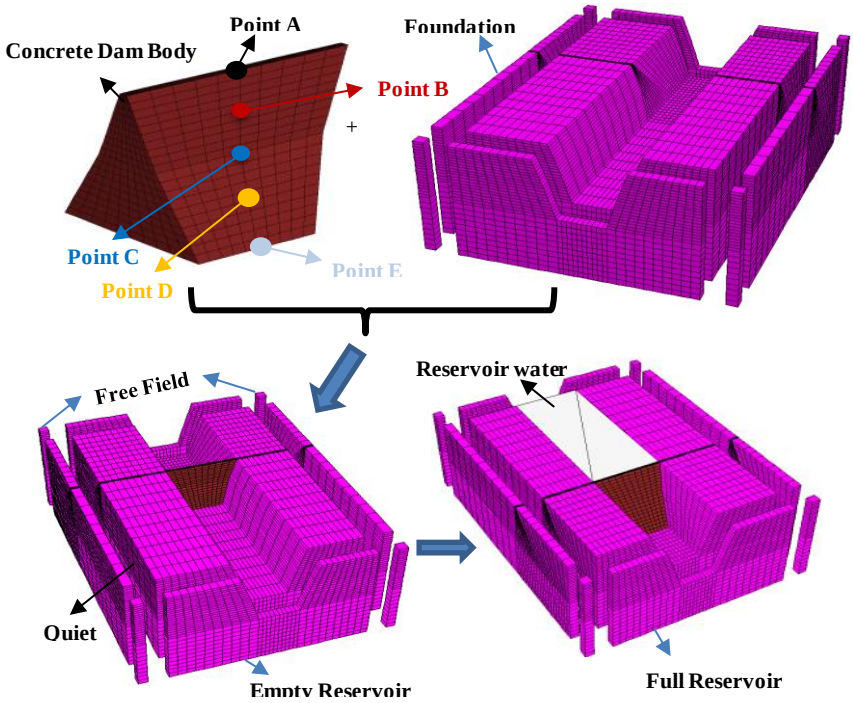

Fig. 3 Three dimensional finite difference model of Boyabat CG dam

Three dimensional finite difference analysis results

When examined the literature, it is clearly seen that there are no many studies related with the effects of different epicenter distances of the earthquake on the nonlinear seismic behaviour of concrete gravity (CG) dams. In order to fill these deficiencies, the nonlinear seismic behaviour of Boyabat CG dam is examined considering 5 various

epicenter distances of earthquake (5 km, 11 km, 24 km, 85 km and 93 km) and these distances are taken into account as Case 1, Case 2, Case 3, Case 4, Case 5 in this study, respectively. Five different nodal points are selected on the dam body surface to better seen changing of nonlinear seismic behaviour of Boyabat CG dam. These nodal points are presented in Fig. 3 in detail. As a result of the seismic analyses, principal stresses, are presented and assessed graphically for these nodal points. In addition, these numerical results are compared with each other.

In Fig. 4, 3D nonlinear seismic principal stress results are shown for 5 nodal points on the dam body surface. Total 5 various epicenter distances are considered in the seismic analyses and principal stress results for Case 1 are presented in Fig. 4a. According to Fig. 4a, maximum principal stress occurred on Point D and its numerical value is -21.1 MPa. It is clearly seen that maximum principal stress does not occur at bottom nodal point of the dam during the earthquake duration for CG dams. The greatest stresses occurred at slightly higher sections of the dam body base. When the other nodal points are examined, the maximum stresses occurred on Points C, E, B and A, respectively. Minimum stress is obtained on Point A (crest point). In Fig. 4b, principal stress values are shown for Case 2. According to Fig. 4b, maximum principal stress occurred on Point D and its numerical value is -15.1 MPa. In addition, minimum stress is observed on Point A. As compared Case 1 and Case 2, it is clearly seen the effects of epicenter distance on the 3D principal stress behaviour of CG dams. When epicenter distance of earthquake increases, principal stress on the dam body surface obviously diminishes. Moreover, maximum principal stresses for other nodal points occurred on Points E, C, B, A, respectively. In Fig. 4c, principal stress results are presented for Case 3. According to Fig. 4c, maximum stress is -12.4 MPa and it occurred on Point D. Moreover, minimum principal stress is observed on Point A (crest point). Maximum principal stress occurred at first seconds of the earthquake and less stress results are obtained for Case 3 as compared with Case 2. In addition, principal stress results for Case 4 are shown in Fig. 4d. Maximum principal stress occurred on Point D and its numerical value is -7.9 MPa. Minimum stress occurred on Point B. During first 10 seconds, there are no significant principal stress values on the dam body surface. According to Fig. 4e, maximum principal stress is observed on Point D and its numerical value is -5.6 MPa. Moreover, no significant stresses did not occur on the dam body surface during first 13 seconds of the earthquake. It is clearly seen from these numerical results that nonlinear maximum principal stresses on the dam body surface obviously increases according from Case 1 to Case 5. In addition, maximum principal stresses for all cases are shown in Table 2.

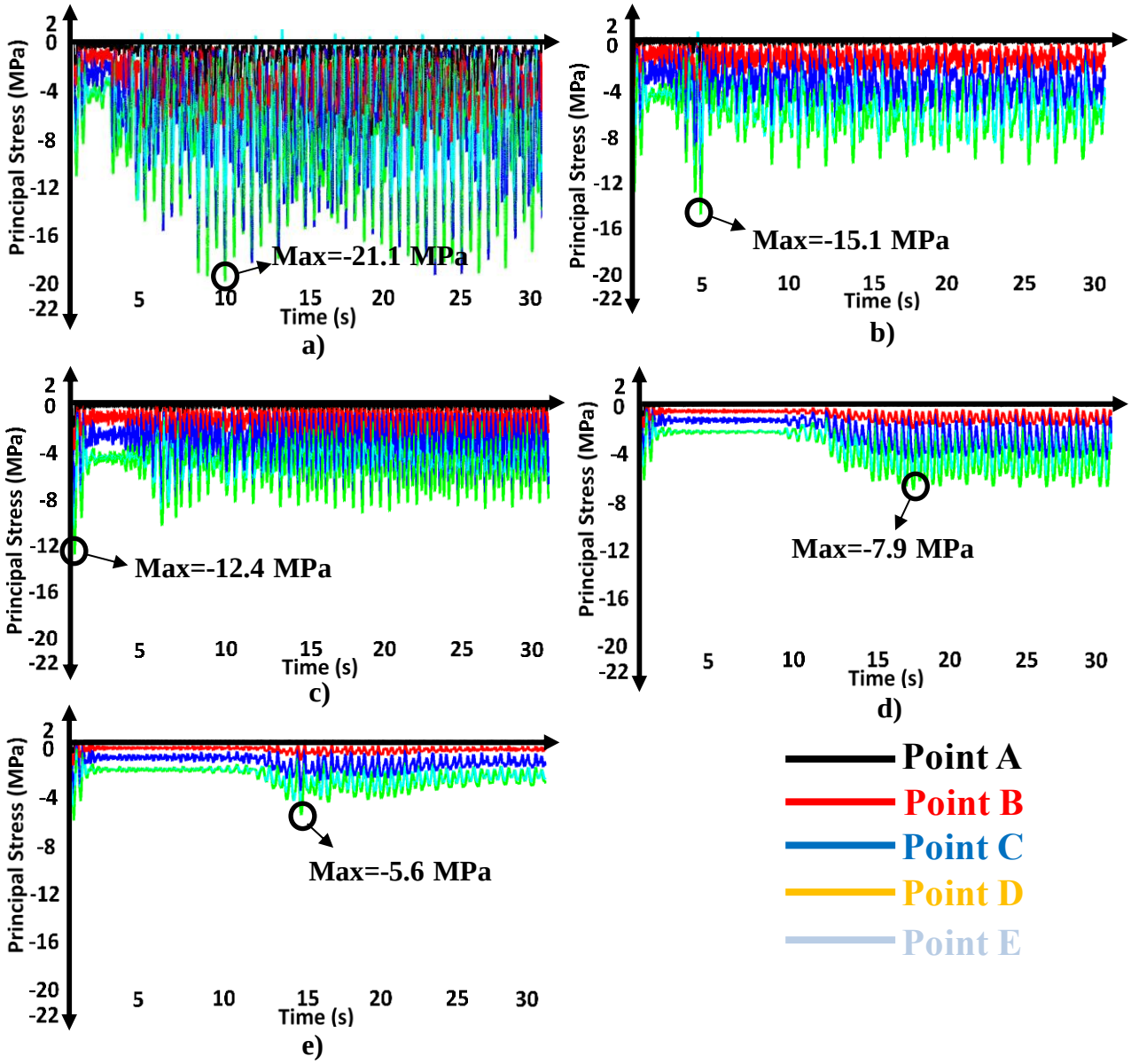

Fig. 4 Seismic principal stress results for a) Case 1 b) Case 2 c) Case 3 d) Case 4 e) Case 5.

Table 2 Maximum principal stresses for all cases

	Case 1	Case 2	Case 3	Case 4	Case 5
Max. Stress (MPa)	-21.1	-15.1	-12.4	-7.9	-5.6

Conclusions

In this paper, three dimensional (3D) nonlinear earthquake behaviour of Boyabat concrete gravity (CG) dam is investigated under various epicenter distances of 1989 Loma Prieta earthquake. These distances are 5 km, 22 km, 24 km, 85 km and 93 km, respectively. These ground motions are defined to 3D finite difference model using special fish functions and nonlinear seismic analyses (principal stresses) of Boyabat CG dam body is assessed as below;

- It is strongly proposed that while modelling or constructing a CG dam, it should not be randomly built and place of the dam should be carefully selected for its safety and future. Moreover, distance of epicenter to the dam should be controlled in detail. It is clearly seen from this study that each epicenter distance has important seismic effects on the earthquake behaviour of CG dams.
- Nonlinear maximum principal stresses on the dam body surface obviously increased from 5 km epicenter distance to 93 km epicenter distance. It is clearly seen that maximum principal stress does not occur at the lowest nodal point of the dam body during the earthquake duration. The greatest stresses occur at slightly higher sections of the dam body base (Point D). When the other nodal points are examined, the maximum stresses occurred on Points C, E, B and A, respectively.

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