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Examination of 3D Finite Difference Analyses of Zonguldak-Kozlu CCR Dam Subjected Strong Ground Motions Considering Dam-Foundation-Reservoir Interaction

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Keywords: Clay Core Rockfill Dam, Finite-Difference Method, Free-Field Boundary Condition, Interaction Problem, Seismic Analysis.

Abstract

Dams are one of the most important water structures built to meet people's vital needs such as irrigation and energy. It is important to examine the seismic safety of important water structures such as dams. In addition, it is vital to investigate the interaction behavior of dams due to the bodies of the dams, the reservoir water, and the foundation being in constant interaction. Therefore, this study investigates the seismic behavior of clay core rockfill (CCR) dams by considering the dam-foundation-reservoir interaction. The Kozlu CCR dam built in Turkey-Zonguldak is chosen for seismic analyses. Three-dimensional (3D) modeling and analysis of the dam are performed utilizing the FLAC3D program. The foundation section is extended down to the dam's height, and free-field and quiet non-reflecting boundary conditions are defined to the lateral boundaries of the foundation. Besides, the fix boundary condition is considered the foundation's base section. The Mohr-Coulomb material model is utilized for dam body material and foundation. Special interaction elements have been assigned between the discrete surfaces. These elements are affected by the 3D model of the dam in the x, y, and z directions. A total of 12 different earthquakes (magnitudes of earthquakes are between 5.9 and 7.6) are used for earthquake analyses. X, Y, and Z directions of ground motion accelerations are defined in the program, and accelerations are applied to the base of the dam. As a result of the earthquake analyses, it is concluded that significant displacement and principal stresses occurred in the dam body for each earthquake. Moreover, it is inferred that the seismic principal stress values occurring in the dam body with interaction elements are smaller than the values observed in the dam body without interaction elements.

1. Introduction

Dams are very important water structures built to meet the vital needs of people. Many types of dams have been built from the past to the present. One of the most important of these dam types is the clay core rockfill (CCR) dam. These dams are the most preferred type of dam in many countries of the world. CCR dams are exposed to many external loads (such as reservoir loads, and earthquake loads) and the structural behavior of these dams can change significantly under external loads. In addition, the bodies of CCR dams are in constant interaction with the reservoir water and the foundation. This interaction situation is vital for the structural behavior of CCR dams. For this reason, examining the interaction behavior of CCR dams is very important for the future and safety of these dams. Turkey is located in a region with high seismicity. There are many fault lines in Turkey and one of the most important of these fault lines is the Northern Anatolian Fault (NAF) line. The NAF is one of the most important strike-slip faults in the world, whose

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seismological-seismic tectonic features are well known, and constitutes one of the most important tectonic elements of Turkey. The Kozlu dam that is the subject of this study is located on the NAF and it is of great importance to examine the seismicity of this dam. Fig. 1 shows the earthquake zone map of Zonguldak, where the Kozlu dam was built. Kozlu Dam was built between 1979-1986 in Turkey-Zonguldak. This dam is located on Ulutan Stream, and it was built to meet the supply of drinking water and industrial water. The body volume of the dam, which is a rock body fill type, is 1,675,000 m³. The height of the dam from the river bed is 60.15 m [28]. Besides, the volume of the lake at a normal water level is 25 hm³. The lake area at normal water level is 1.07 km². The dam provides 19 hm³ of drinking water per year [28]. Moreover, the depth of the dam body changes along the crest of the dam. A general view of the Kozlu dam is presented in Fig. 2. Also, the most critical section of the dam is shown in detail in Fig. 2. Material properties of the Kozlu dam are shown in Table 1.

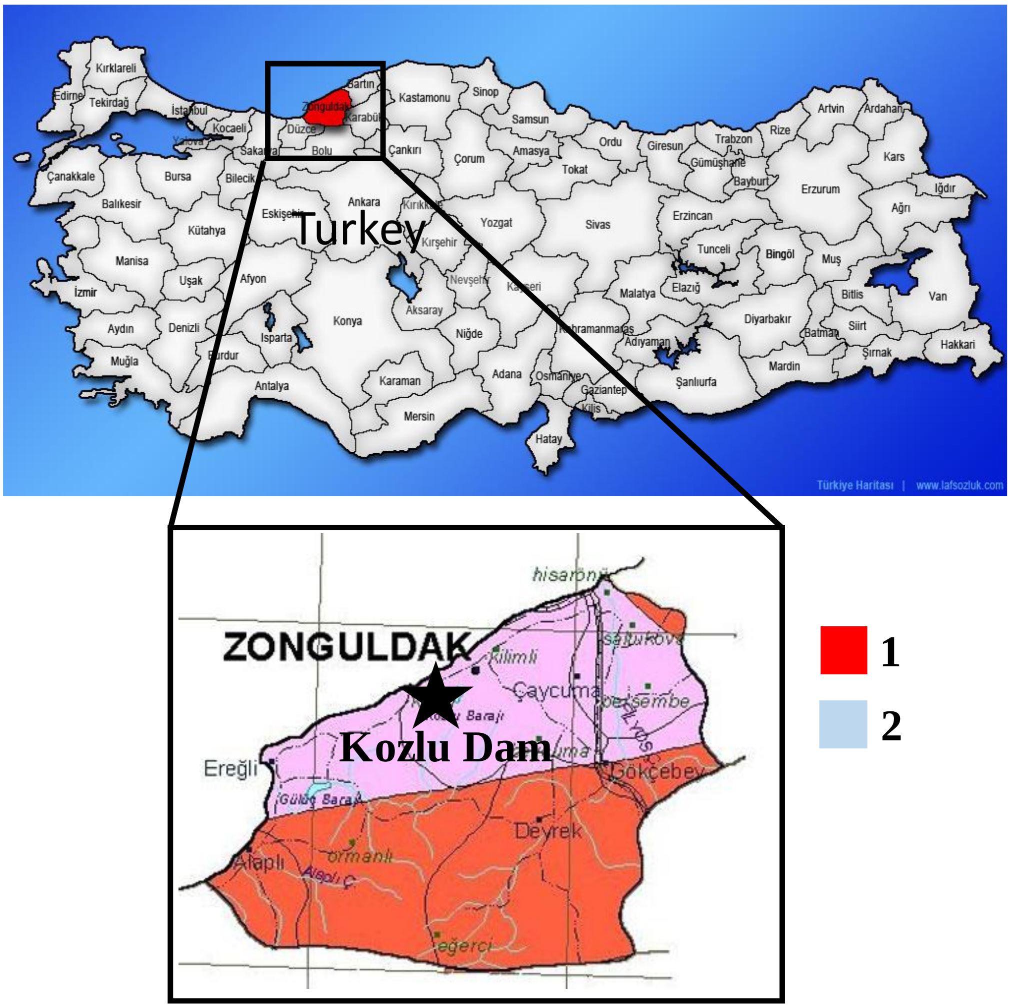


Figure 1. Earthquake zone map of Zonguldak [25].

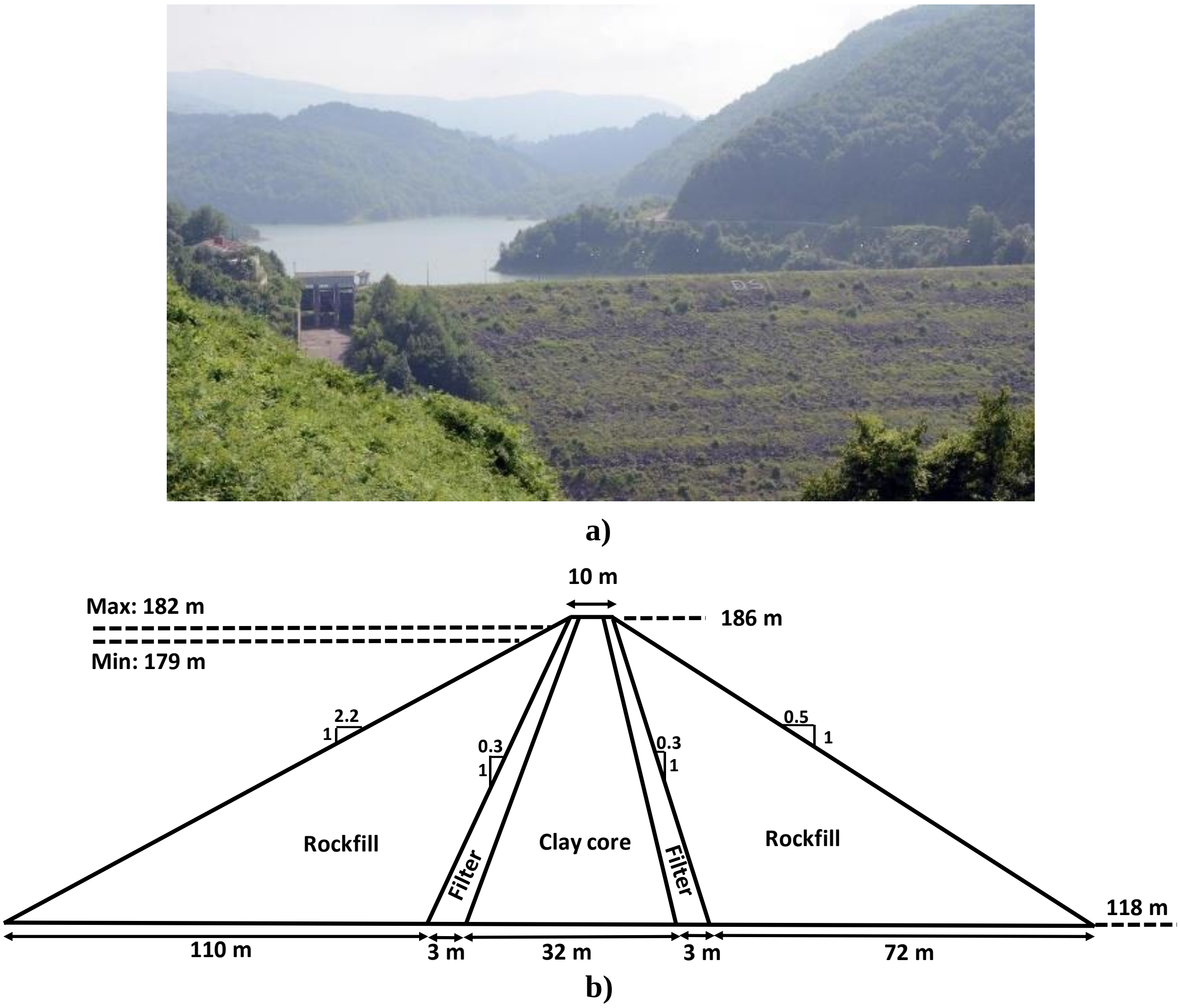


Figure 2. a) General view of Kozlu dam b) the most critical section of the Kozlu dam [28].

Table 1. Material properties of the dam body [28].

Mat.	Den.	Por.	Wat. Cont.	Air cont.	Mat. Cont.	Shear Mod.
Unit	g/cm^3			%		GPa
Filter	2.74	18.61	4.05	14.56	81.39	25
Clay	2.68	25.75	7.78	17.97	74.25	-
Rockfill	3.01	25.25	1.50	23.75	74.75	32

In the literature, many studies have been carried out on the structural behavior of CCR dams. Cetin et al. (2000) examined the settlement behavior of clay core rockfill dams by considering measurement results. According to displacement results on the dam body, it was concluded that the largest settlement value observed on the dam body is 2.5 m [1]. Zhang and Chen (2006) investigated the seepage behavior of rockfill dams considering reservoir problems. It was seen that the seepage behavior of rockfill dams may change over time [2]. Sharp and Adalier (2006) assessed the seismic response of rockfill dams taking into account 3 various liquefiable foundation layers. As a result of this study, very important numerical results about the liquefaction behavior of the CCR dam were obtained [3]. Unal et al. (2007) examined the leakage behavior of rockfill dams. It was seen that after impoundment, total leakage in the dam had been directly affected by reservoir water [4]. Tosun et al. (2007) investigated the seismic hazard behavior of rockfill dams in Turkey. It was inferred that fifteen large rockfill dams in Turkey must be analyzed with high priority and redesigned to increase the safety of the embankments [5]. Oyanguren et al. (2008) evaluated the stability analyses of rockfill dams using in situ direct shear tests. It was seen that in situ testing permits the behavior of the dams to be predicted more accurately [6]. Sica et al. (2008) examined the seismic behavior of rockfill dams considering the effects of past loading history. Ground motion acceleration and displacement time histories on the rock materials of the rockfill dam were measured for the 14/3/1979, 19/9/1985, and 30/5/1990 earthquakes and measurement results were compared with 2D finite element analysis results using the GEFDYN code [7]. The earthquake displacement ground motion behavior of rockfill dams was investigated taking into account special material models and numerical modeling [8-9]. Liu et al. (2012) evaluated the nonlinear principal stress (PS) and strain behavior of clay core rockfill dams. It was concluded that the proposed design for CCR dams is reasonable since no abnormal stresses and deformations occurred in the dam [10]. Yang and Chi (2014) examined the seismic stability behavior of rockfill dams considering the finite element method. A finite element limit analysis was developed and applied to two various types of rockfill dams using the algorithm software SDPT3 [11]. Mahinroosta et al. (2015) examined the collapse vertical displacement on high rockfill dams. A two-dimensional finite element model of the dam was created and it was seen that the highest collapse settlement during the first impounding is 0.8 cm. Moreover, it was concluded that the highest settlement in the dam body after phase II impounding is 2.25 m [12]. Albano et al. (2015) investigated the seismic behavior of bituminous-faced rockfill dams. The dam was modeled as three-dimensional and the numerical models were validated with centrifuge tests [13]. Liu et al. (2016) evaluated the stress-deformation analyses of the cut-off wall in clay-core rockfill dams. It was seen that the highest settlement and highest PS on the dam after impounding are 170 cm and 3 MPa, many intelligent methods. It was seen that intelligent methods are appropriate tools to solve problems with complex mechanisms and many factors, such as the prediction of the settlement of dams [15]. Han et al. (2016) examined the seismic response of rockfill dams using finite-element modeling. It was concluded that the acquired seismic deformations of the Yele rockfill dam are in agreement with field observations [16]. Park and Kim (2017) examined the earthquake behavior of cored rockfill dams' dynamic centrifuge modeling. The experimental tests for soil-cement mixture specimens were performed and the results helped to evaluate the seismic safety of core rockfill dams [17]. He et al. (2021) investigated the crack behavior of embankment dams using the scaled boundary finite element method. It was inferred that post-construction settlements are more critical than settlements during construction for the development of tensile cracking [18]. Wu et al. (2021) assessed the seismic performance of earth dams considering various pulse-like ground motions and non-pulse-like ground motions. The two-dimensional finite element model was created using free-field boundary conditions. According to numerical analysis results, it was seen that pulse-like and non-pulse-like earthquakes have different seismic effects on the earthquake behavior of rockfill dams [19]. As can be seen from studies in the literature [1-24], it is seen that the seismic behavior of CCR dams has not been examined considering the dam body-reservoir water-foundation interaction. In this study, to fill this gap in the literature, the seismic behavior of the Kozlu CCR dam, which was built in Turkey-Zonguldak and meets the irrigation needs of Zonguldak and surrounding provinces, was investigated in detail. First, the dam body model and the foundation were created with the help of the Fast Lagrangian Analysis of Continua 3D (FLAC3D) program based on the finite-difference method. While creating the body model of the dam, attention was paid to modeling the clay core and rockfill materials in the body following the project. After the dam body was modeled, the foundation section of the dam was created. The Mohr-Coulomb material model was used for the dam body and foundation section. Free-field and quiet boundary conditions were defined for the lateral boundaries of the dam model. Besides, the reflecting (fix) boundary condition was taken into account in the base section of the 3D model of the dam. Special interaction elements were defined between the dam body-reservoir water and the foundation in the x, y, and z directions. A total of 12 different earthquakes were utilized for the seismic analysis of the dam. As a result of the seismic analysis of the dam, important information was obtained about the interaction problems between the discrete surfaces of clay core rockfill dams. Moreover, it was observed how the interaction elements between the discrete surfaces changed the seismic behavior of clay core rockfill dams.

2. Three-Dimensional Modelling of Kozlu Dam

Examining the structural and seismic behavior of important water structures such as dams is of great importance for the safety and future of these structures. In this section, detailed information about the three-dimensional (3D) modeling of the Kozlu clay core rockfill (CCR) dam is presented in detail. Kozlu CCR dam has a large clay material in the middle of the body. While modeling, firstly, the clay material part was created. After the geometry of the clay material was generated, the rock fill material was modeled. Clay core and rockfill material were created following the dam project. After the dam body was formed, the meshing process was performed and the dam was subjected to creep analysis. According to the creep displacement results of the dam, the optimum mesh range was selected. The FLAC3D program provides special material models and fish functions to model the creep behavior of geotechnical structures over time. In this study, the mesh range of the Kozlu dam model was obtained using time-dependent creep analyses, not random ones. Before the seismic analysis, 10 different creep analyzes of the dam were made. Different mesh ranges were used for 10 different creep analyses. Different creep displacements were obtained in the dam body for each mesh range. However, creep displacements in the dam body did not change after a certain mesh range. For this reason, the optimum mesh range of the dam was determined by considering the critical mesh ranges. According to the creep analyses, the optimum mesh range of the Kozlu dam is 11.5 m. The foundation section of the dam is extended downwards as far as the dam body. Moreover, towards the right and left sides of the dam, the foundation section was extended as far as the dam body. Finally, in the upstream and downstream parts of the dam, the foundation part was extended 3 times and 1 time of the height of the dam, respectively. The reservoir part was created considering the highest water level of the dam. In the dam model, special spring interaction elements are defined between the discrete surfaces (dam body-reservoir water-foundation). The mechanical properties of these elements are defined in the FLAC3D program with the help of special fish functions. A fish function is used by naming an input line according to the researchers' intended use. Fish functions are utilized to create geometry, material property, boundary conditions, and all the structures. Moreover, fish functions are created by users using codes suitable for the FLAC3D programming language. Users can model all structures and grounds thanks to the fish functions. Interaction elements are defined in the x, y, and z directions. Thanks to these interaction elements, important information about the interaction problems of clay core rockfill dams have been presented. The value of the interaction elements defined between the discrete surfaces is 10^8 Pa/m [27]. Then, the Mohr-Coulomb material model was defined for the clay core, rockfill, and foundation parts of the dam. The Mohr-Coulomb material model is generally used for many rockfill materials in the FLAC3D software [31]. In this material model, PS ($\sigma_1;\sigma_2;\sigma_3$) is used for the out-of-plane PS ($\sigma_{ZZ} and \sigma_{YY}$). Moreover, the failure criterion is defined in the plane $\sigma_1;\sigma_3$ as seen in Fig. 3 [26]. In this study, the density, shear modulus, and bulk modulus of the dam body and foundation materials are defined in the FLAC3D program.

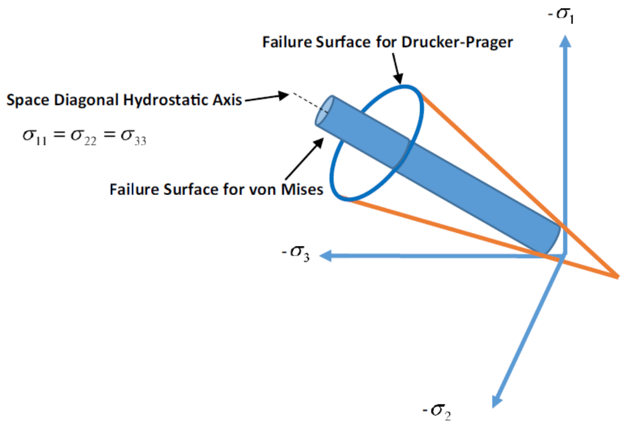


Figure 3. Mohr-Coulomb failure criterion [26, 31].

Considering the material parameters of the dam (G/Gmax), special hysteresis damping is calculated for each material and the calculated damping rates are defined in the FLAC3D. Free-field and quiet non-reflecting boundary conditions are taken into account on the lateral surfaces of the dam model. With the help of these non-reflecting boundary conditions, the back reflections of earthquake waves in the model are prevented. Furthermore, realistic seismic analysis results are obtained with the help of these boundary conditions. Free-field and quiet non-reflecting boundary conditions ensure that the earthquake waves do not reflect inside the structure and allow us to obtain more accurate earthquake results. The free-field boundary condition is placed on the side boundaries to minimize wave reflections. Moreover, in the quiet boundary condition, the earthquake dashpots are considered and the normal and shear earthquake dashpots are calculated. Fix boundary conditions are considered at the base of the dam model. The three-dimensional model of the dam and the modeling stages are shown in Fig. 4 in detail. Moreover, the general views of the interaction elements defined on the discrete surfaces between the dam body, reservoir water, and foundation are presented in Fig. 5. A total of 12 different strong ground motions (magnitudes are between 5.9 and 7.6) were utilized in seismic analysis (Table 1). Earthquake accelerations are defined to the FLAC3D program. Moreover, the flow chart for the modeling of the Kozlu dam is shown in Fig. 6.

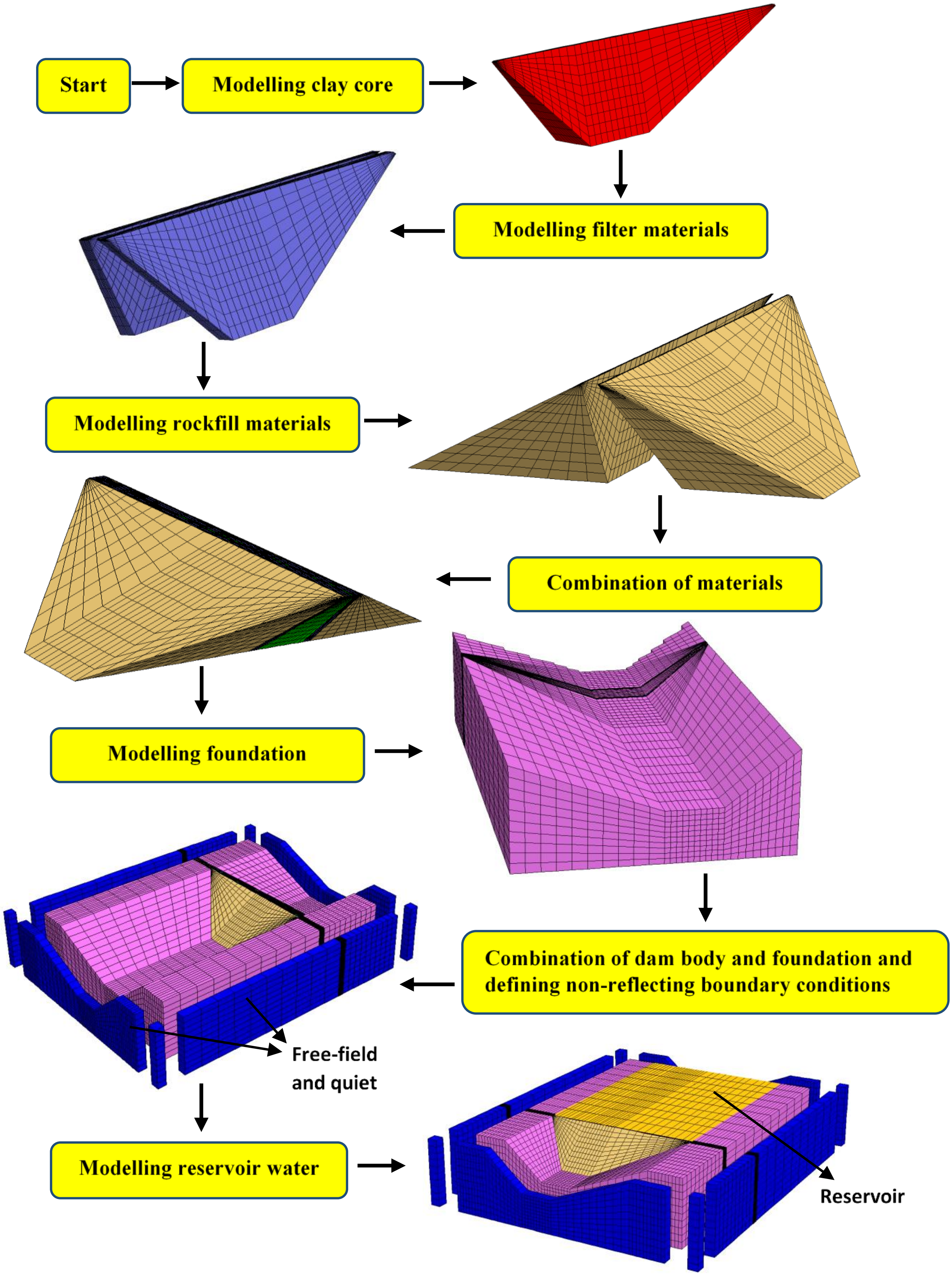


Figure 4. Modeling Kozlu clay core rockfill dam.

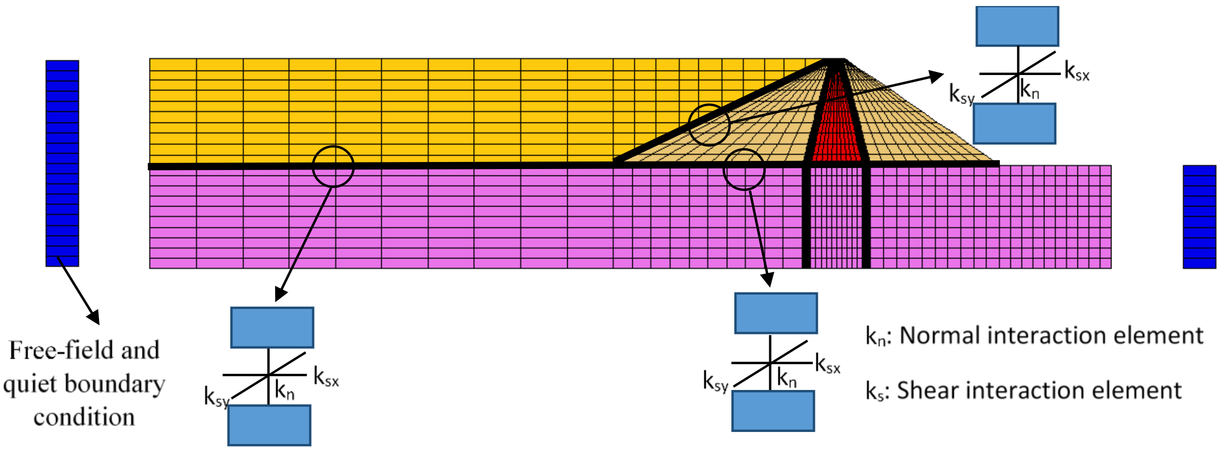


Figure 5. View of interaction elements between discrete surfaces.

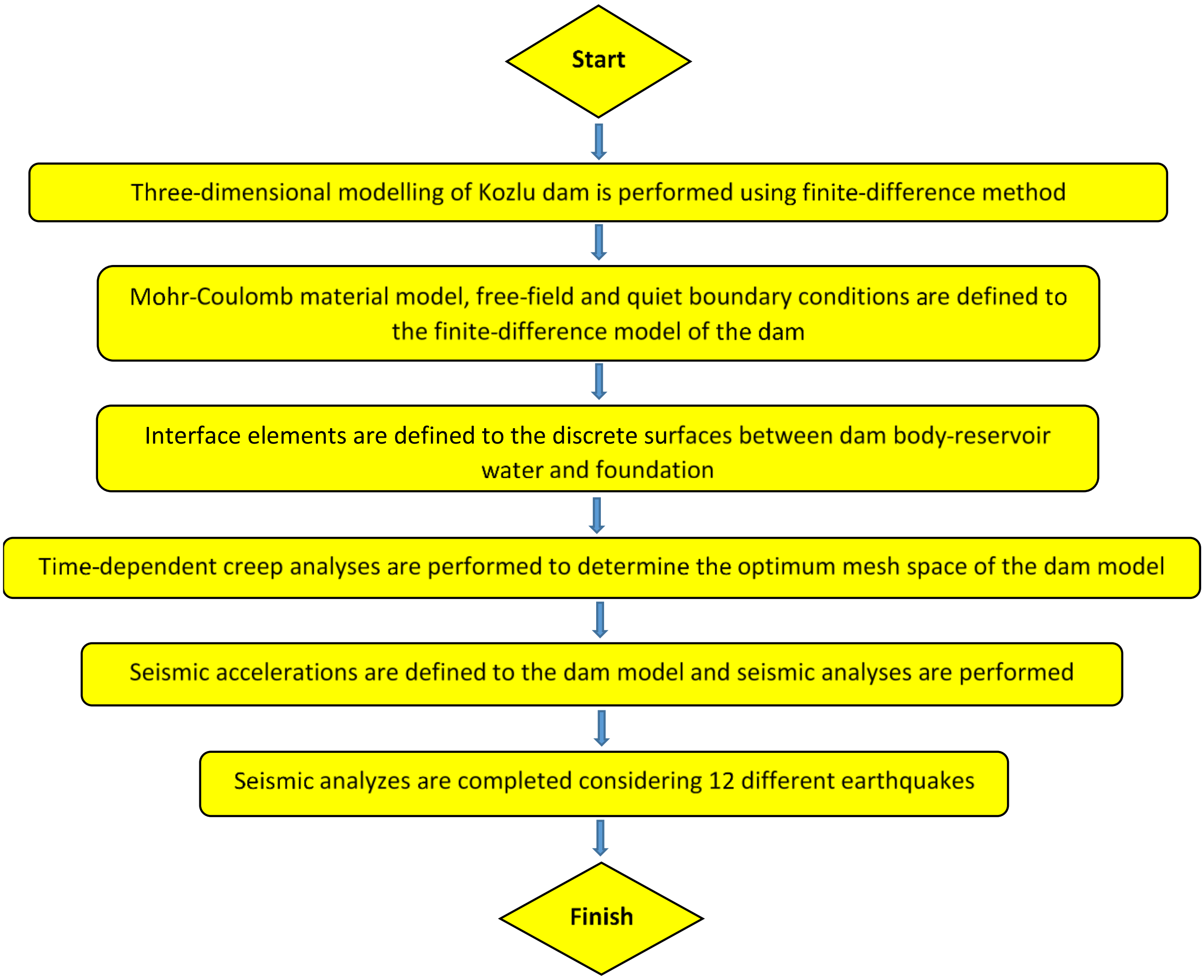


Figure 6. Flow chart for the modeling Kozlu dam.

3. Results and Discussion

In this section, the seismic behavior of the Kozlu clay core rockfill (CCR) dam is investigated under 12 different earthquakes. After the 3D model is created, earthquake accelerations in the x, y, and z directions are applied to the base of the dam model. These earthquake accelerations are defined in the FLAC3D program. The characteristic properties of 12 different earthquakes used in seismic analyzes are shown in Table 2 in detail. Earthquake data are obtained from PEER [29] and AFAD [30]. Furthermore, the earthquake data are acquired from important earthquakes that have occurred both in Turkey and in many countries of the world. Kozlu dam was built on the Northern Anatolian fault line. For this reason, attention is paid to ensuring that earthquake magnitudes used in seismic analyses should not be below 6.0. Seismic analyzes are performed for a total of 2 different situations (Table 3).

The situation where interaction elements are not defined between discrete surfaces is called "Situation A". In addition, the "Situation B" definition was made for the case of defining the interaction elements between the discrete surfaces. In Fig. 8, the seismic principal stress (PS) results of the Kozlu dam are presented graphically. The PS results shown in the graphs are obtained from Point A at the base of the upstream section of the dam (Fig. 7).

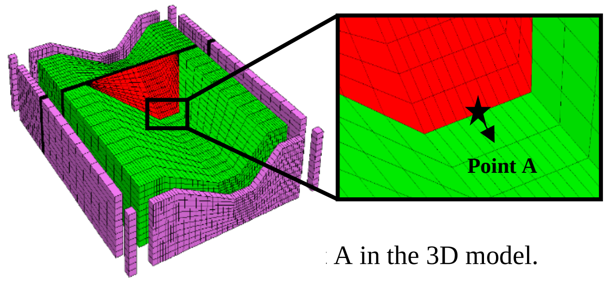


Figure 7. View of Point A in the 3D model.

Table 2. Characteristic properties of earthquakes [29, 30].

Case	EQ	Year	M_w	d (km)	PGA	Ap/Vp	TP
1	Chi-Chi	1999	7.6	3.2	0.12	3.18	4.4
2		1999	7.6	1.1	0.46	1.72	10.9
3	Kobe	1995	6.9	0.6	0.82	9.93	0.9
4	Northridge.	1994	6.7	6.2	0.61	5.11	2.5
5	Cape Mend.	1992	7.1	18.5	0.39	8.7	1.2
6		1992	7.1	9.5	0.66	7.19	0.7
7	Loma Pr.	1989	6.9	13.0	0.32	7.30	3.1
8	Sup. Hills	1987	6.6	0.7	0.45	3.94	2.2
9	N. Palm Spr..	1986	6.0	8.2	0.59	7.93	1.4
10	Imp. Val.	1979	6.5	4.2	0.36	4.59	4.3
11	Kocaeli	1999	7.6	17	0.42	1.88	9.7
12	Düzce	2022	5.9	6.8	0.59	7.86	1.3

Table 3. Various situations for seismic analyses.

Situation	Describing
A	Without interaction elements
B	With interaction elements

According to Fig. 8, it is seen that the greatest PS values occurring in Point A are different from each other for Situation A and Situation B. For Case 1 earthquake, the largest PS values for Situation A and Situation B are 5.87 MPa and 1.83 MPa, respectively (Fig. 8a). This result clearly shows the effects of interaction elements on the seismic behavior of CCR dams. During the Case 2 earthquake, the greatest PS value for Situation A is 8.1 MPa. Moreover, for Situation B, the highest PS value observed in Point A is 3.2 MPa (Fig. 8b). For the Case 3 earthquake, the highest PS values for Situation A and Situation B are 4.3 MPa and 1.1 MPa, respectively (Fig. 8c). During the Case 4 earthquake, the maximum PS value for Situation A is 4.2 MPa. Besides, for Situation B, the highest PS value on Point A is 1.7 MPa (Fig. 8d). For the Case 5 earthquake, the maximum PS values on Point A for Situation A and Situation B are 7.1 MPa and 2.3 MPa, respectively (Fig. 8e). This result clearly shows that different earthquakes significantly change the interaction behavior of CCR dams. During the Case 6 earthquake, it is seen that the greatest PS value for Situation A is 8.9 MPa. When Cases 1-6 are compared with each other, it is seen that the highest PS value occurred on the dam is observed for Case 6 earthquake (Fig. 8f). During the Case 7 earthquake, the greatest PS value for Situation A is 5.6 MPa. Furthermore, the highest PS value in the dam body for Situation B is 1.4 MPa (Fig. 8g). For Situation A and Situation B, the greatest PS values obtained on the Kozlu dam body during the Case 8 earthquake are 4.4 MPa and 1.3 MPa, respectively (Fig. 8h). In addition, for the Case 9 earthquake, the highest PS value for Situation A is 8.1 MPa (Fig. 8i). Finally, the highest PS values obtained at the base of the Kozlu dam during the Case 10 earthquake are 7.4 MPa and 2.5 MPa for Situation A and Situation B, respectively (Fig. 8j). Then, the seismic ground motion behavior of the Kozlu dam is shown for 1999 Kocaeli earthquake in Fig. 8k. According to Fig. 8j, it is seen that the maximum PS value occurring on the dam body without interaction elements is 8.1 MPa. Besides, for dam with interaction elements, the greatest PS value observed on the dam body is 1.7 MPa (Fig. 8k). In Fig. 8l, numerical analysis results of the dam are presented for the 2022 Düzce earthquake. This earthquake occurred in Düzce, Turkey in 2022. For this reason, this earthquake analysis is very important for evaluating the structural behavior of the Kozlu dam. According to Fig. 8l, the maximum PS value on the dam body without interaction elements is 4.2 MPa. Furthermore, when both situations of the dam are compared, fewer PS values are observed on the dam body for the dam with interaction elements.

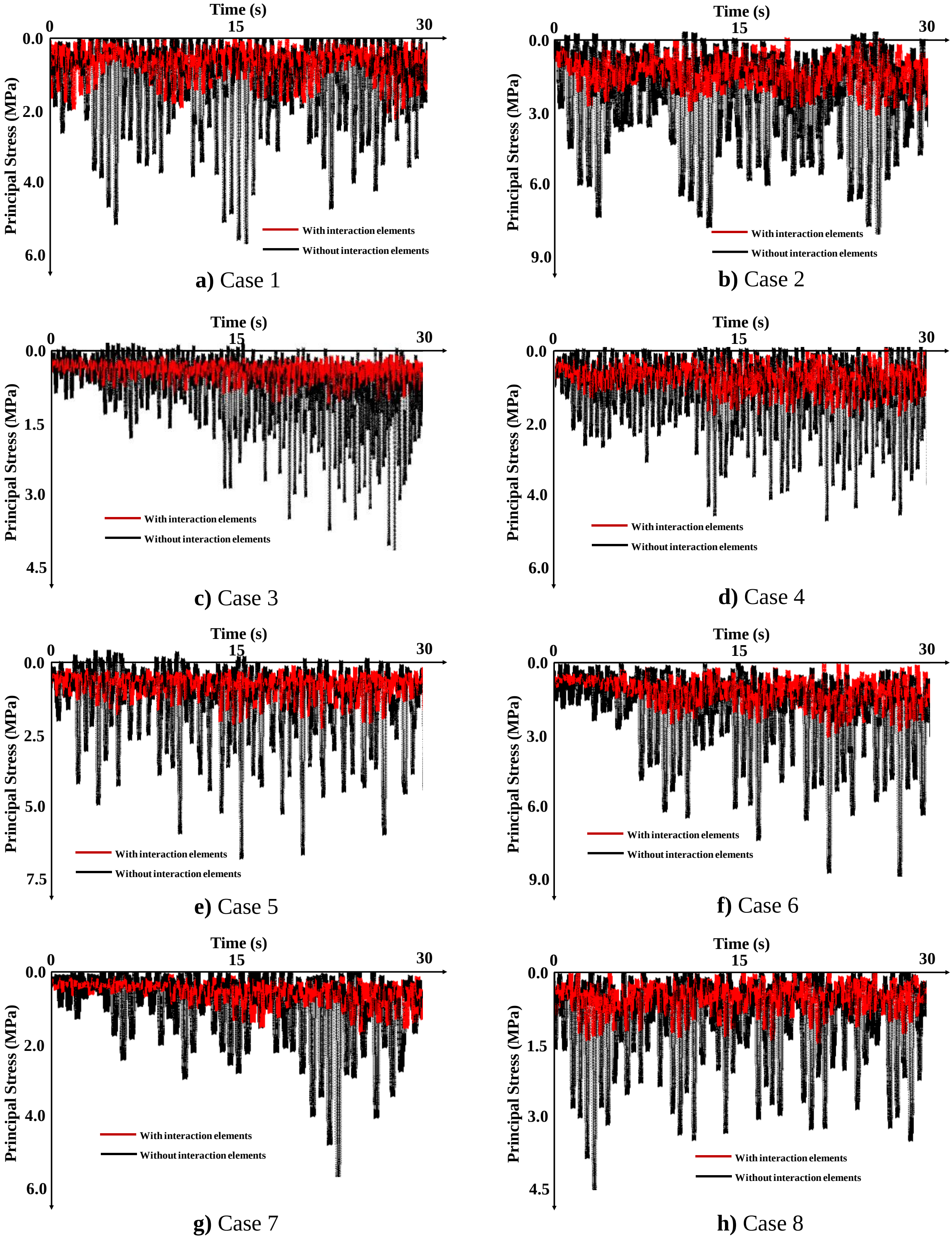
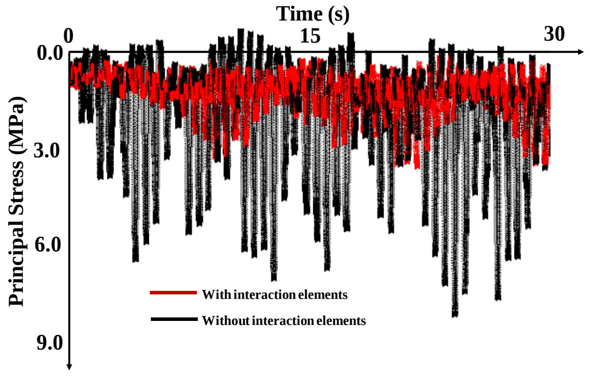
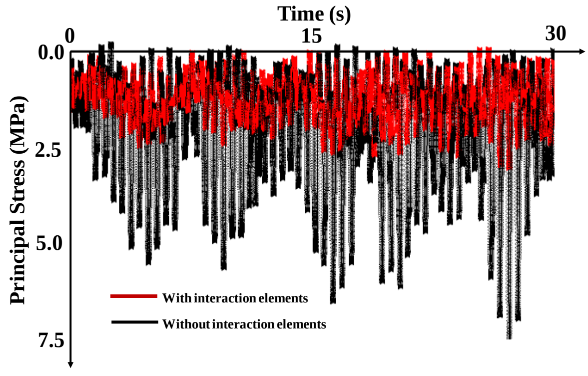


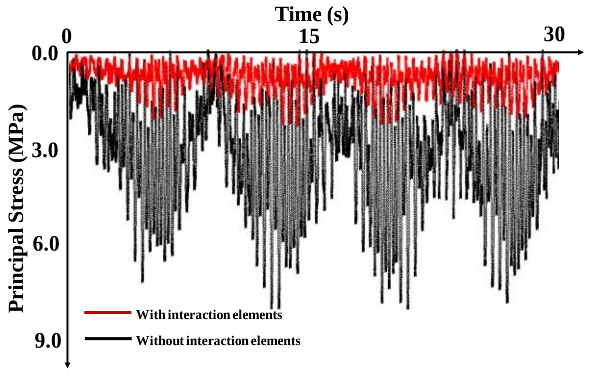
Figure 8. Seismic PS results on Point A for 12 various earthquakes.



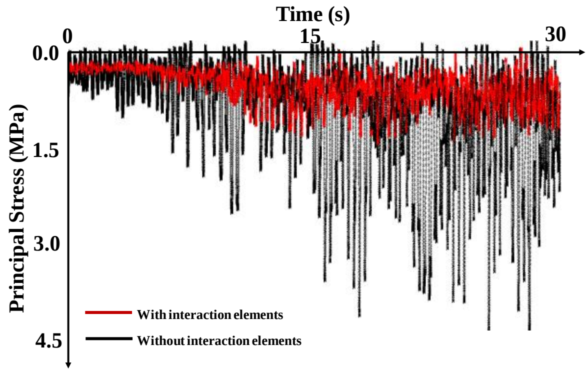
i) Case 9



j) Case 10



k) Case 11



l) Case 12

Figure 8. Continuing.

According to the seismic PS results, it is seen that the highest PS values that took place on the dam body for Situation A are approximately 2 times that of Situation B. This result shows the importance of interaction elements between discrete surfaces in CCR dams. In Fig. 9, the earthquake behavior of the Kozlu dam is examined with the help of contour diagrams. Contour diagrams are presented for 12 different earthquakes, and these diagrams are shown separately for Situation A and Situation B. According to Fig. 9a, the highest PS values for Case 1 are observed in the middle parts of the dam body. Besides, minimum PS values are acquired on the crest of the dam. When the two-dimensional contour of the dam is examined, it is seen that significant PS values occurred in the clay core of the dam (Fig. 9a). Moreover, for Situation B, the highest PS values are observed in the lateral sections of the Kozlu dam body and significant PS values are gained in the clay core of the dam (Fig. 9b). In Fig. 10, the seismic PS behavior of the dam is examined for Case 2. According to Fig. 10, the highest PS values for Situation A are obtained in the middle sections of the dam body. In addition, fewer PS values are observed in the side sections of the dam as compared to the middle sections of the dam. For Situation B, significant PS values took place in the clay core of the dam (Fig. 10b).

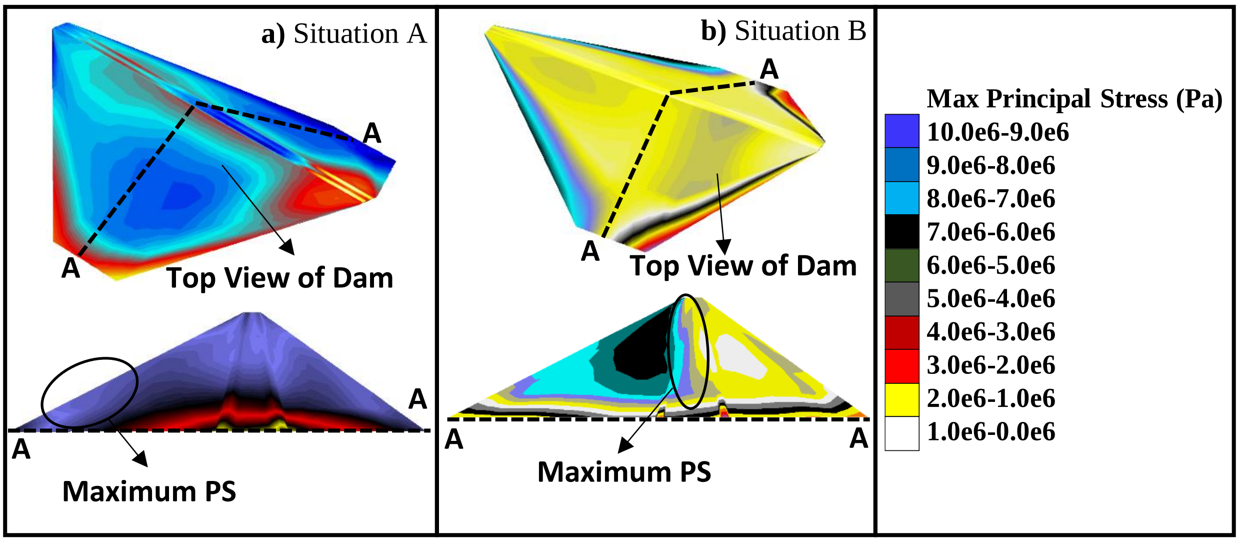


Figure 9. Seismic contours for Situation A and Situation B (Case 1).

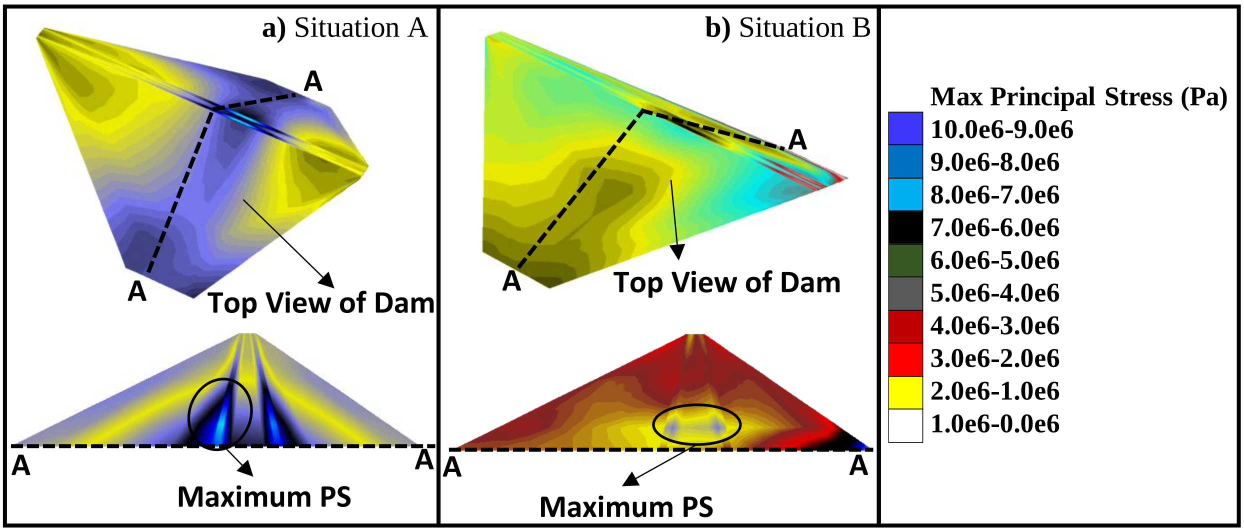


Figure 10. Seismic contours for Situation A and Situation B (Case 2).

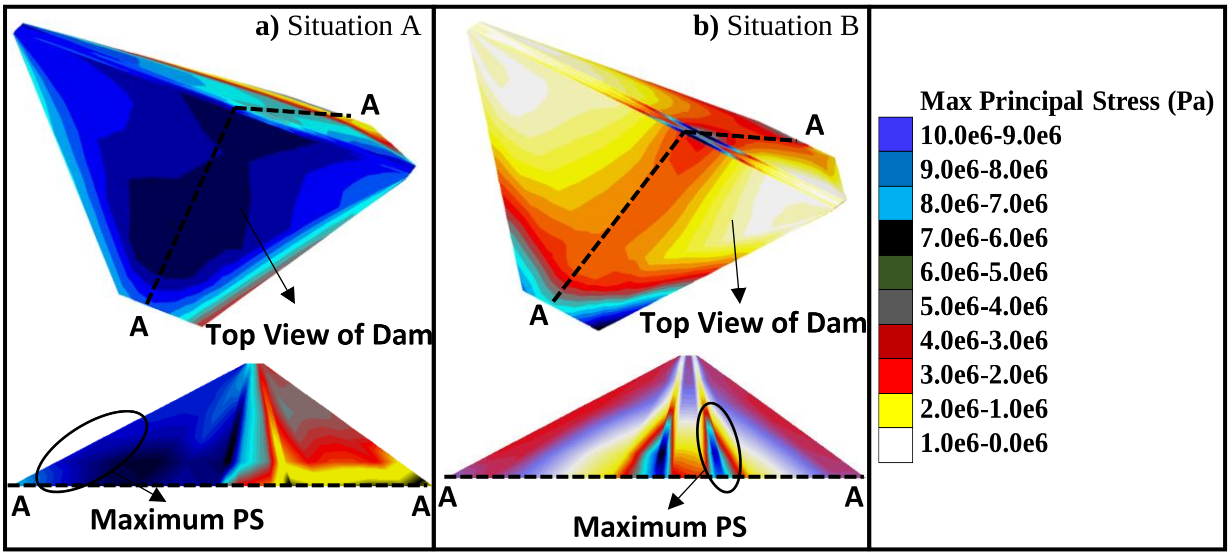


Figure 11. Seismic contours for Situation A and Situation B (Case 3).

In Fig. 11, the seismic behavior of the Kozlu dam is examined for Case 3. It is concluded that the PS values occurring in the dam body for Situation A and Situation B are very different from each other. For Situation A, it is observed that higher PS values occurred in the upstream parts of the dam than in the downstream parts. Moreover, for Situation B, higher PS values are acquired around the clay core material of the dam as compared to the other sections. This result shows the importance of the interaction situation between the discrete surfaces of CCR dams. During the Case 4 earthquake, the highest PS values for Situation A took place in the upstream parts of the dam. Approximately 10 MPa highest PS values are observed in the middle parts of the dam. For Situation B, 7.2 MPa PS values are acquired around the rockfill material of the dam. Besides, approximately 5 MPa PS values occurred around the clay core material (Fig. 12). In Fig. 13, the seismic PS behavior of the Kozlu CCR dam is investigated for the Case 5 earthquake. For Situation A, approximately 8 MPa PS value is obtained in the middle sections of the dam body. Moreover, significant PS values are observed at the base of the dam (Fig. 13a). For Situation B, serious PS values are obtained around the rockfill and clay core materials. During the Case 6 earthquake, the highest PS values for Situation A took place at the lower sides of the dam body. Furthermore, significant PS values are observed around the clay core material for Situation B. It is clear from this result that the clay core material is of great importance for the PS behavior of CCR dams. During the Case 6 earthquake, significant PS values are obtained at the base of the dam. Fewer PS values occurred in the downstream parts of the dam as compared to the upstream parts. For Situation B, approximately 9 MPa maximum PS value is observed around the clay core material of the Kozlu dam (Fig. 14b). In Fig. 15, the PS behavior of the dam is presented for the Case 7 earthquake in detail. For Situation A, higher PS values occurred at the bottom of the upstream part of the dam when compared to other parts of the dam. Besides, significant PS values are acquired at the base of the dam for Situation B (Fig. 15b). Furthermore, about 6 MPa PS value is observed around the clay core material of the dam. Fig. 16 shows the seismic behavior of the dam for Case 8. During the Case 8 earthquake, approximately 9 MPa PS value is acquired around the clay core material of the dam for Situation A. Besides, significant PS values are observed in the upstream parts of the dam. For Situation B, approximately 8 MPa PS values occurred on the underside of the clay core material of the dam (Fig. 16b). From these results, it is seen how the interaction elements defined between the discrete surfaces of the dam change the seismic behavior of CCR dams.

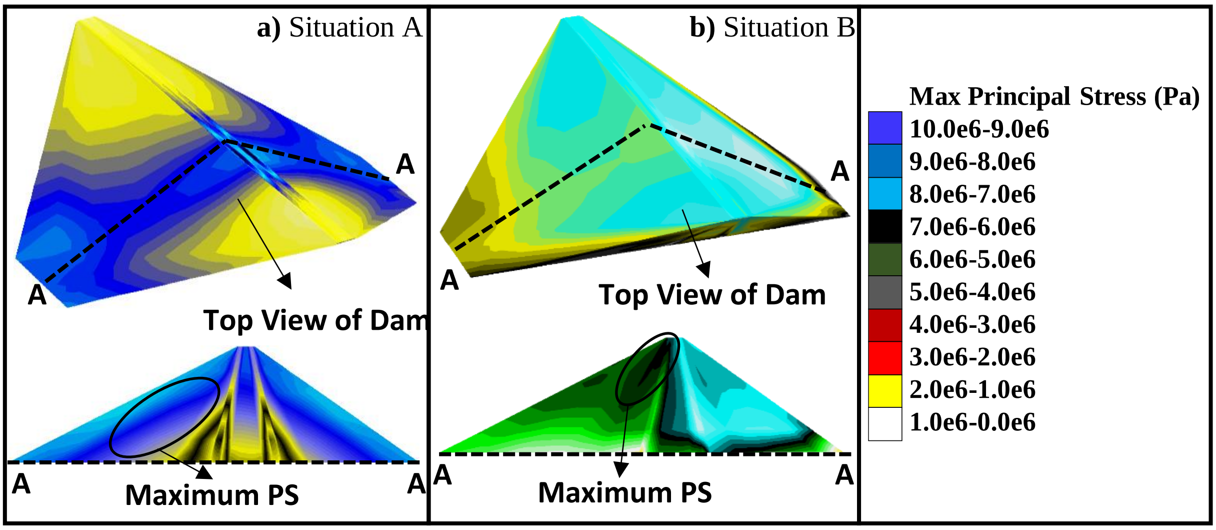


Figure 12. Seismic contours for Situation A and Situation B (Case 4).

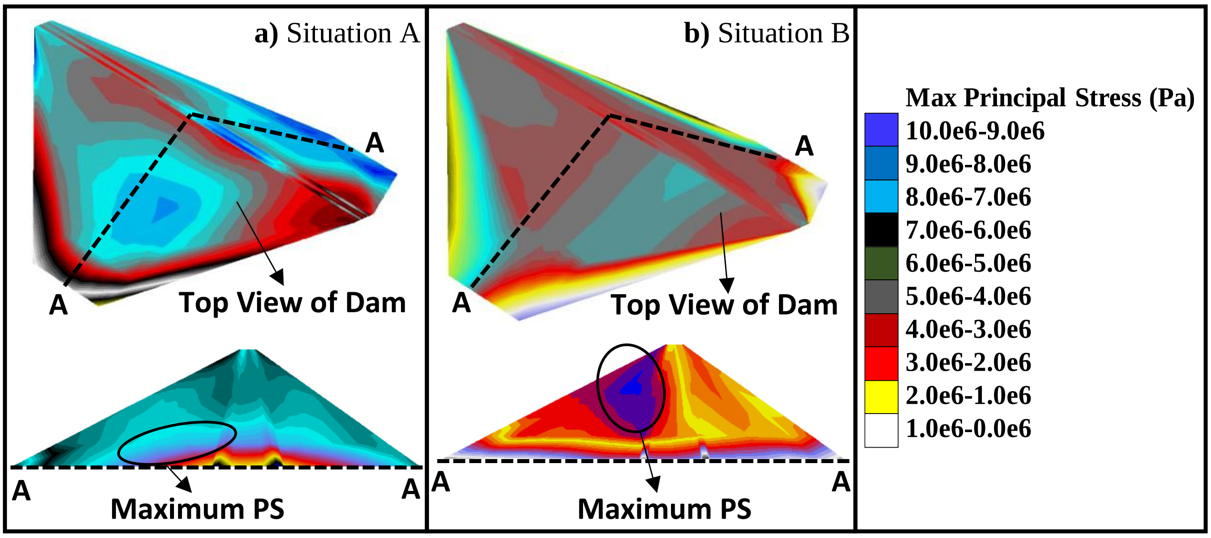


Figure 13. Seismic contours for Situation A and Situation B (Case 5).

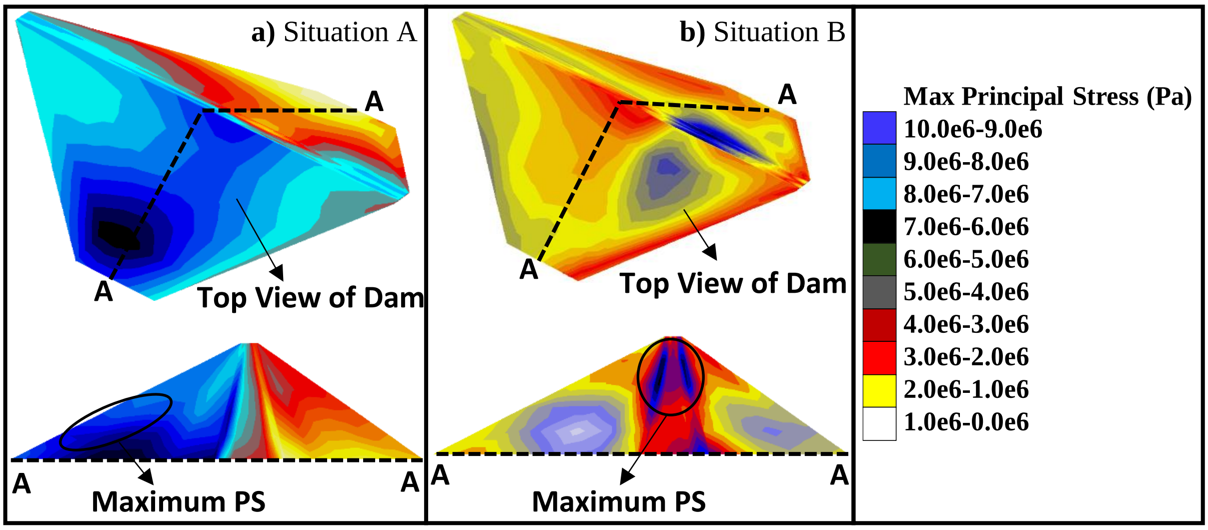


Figure 14. Seismic contours for Situation A and Situation B (Case 6).

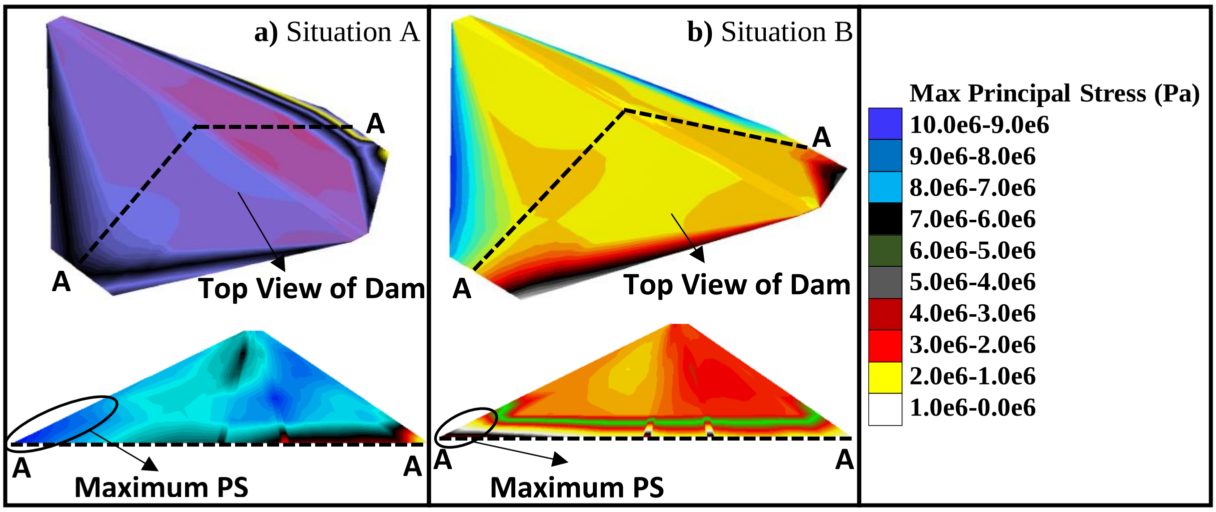


Figure 15. Seismic contours for Situation A and Situation B (Case 7).

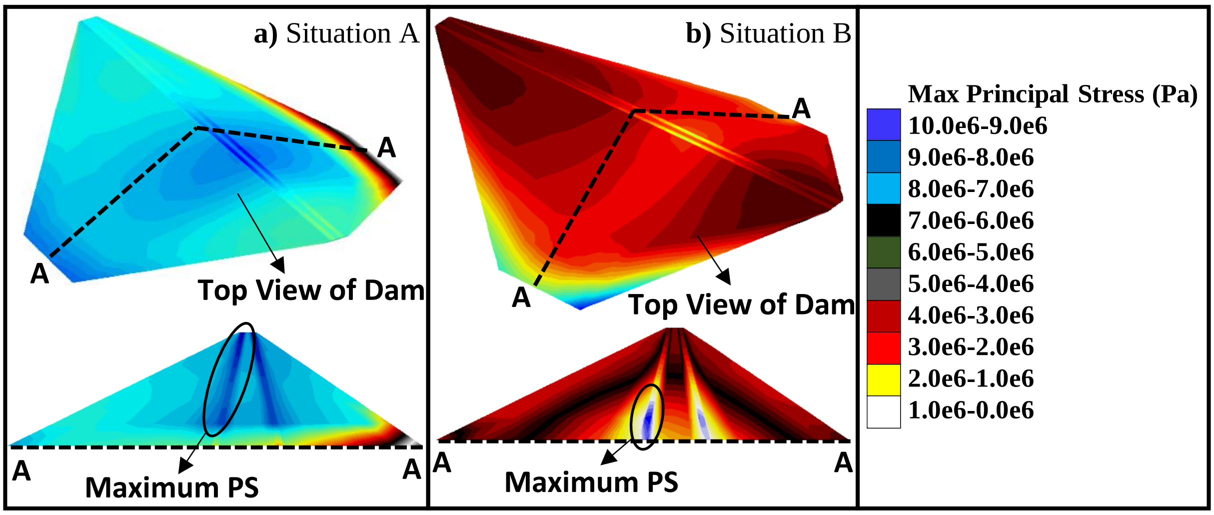


Figure 16. Seismic contours for Situation A and Situation B (Case 8).

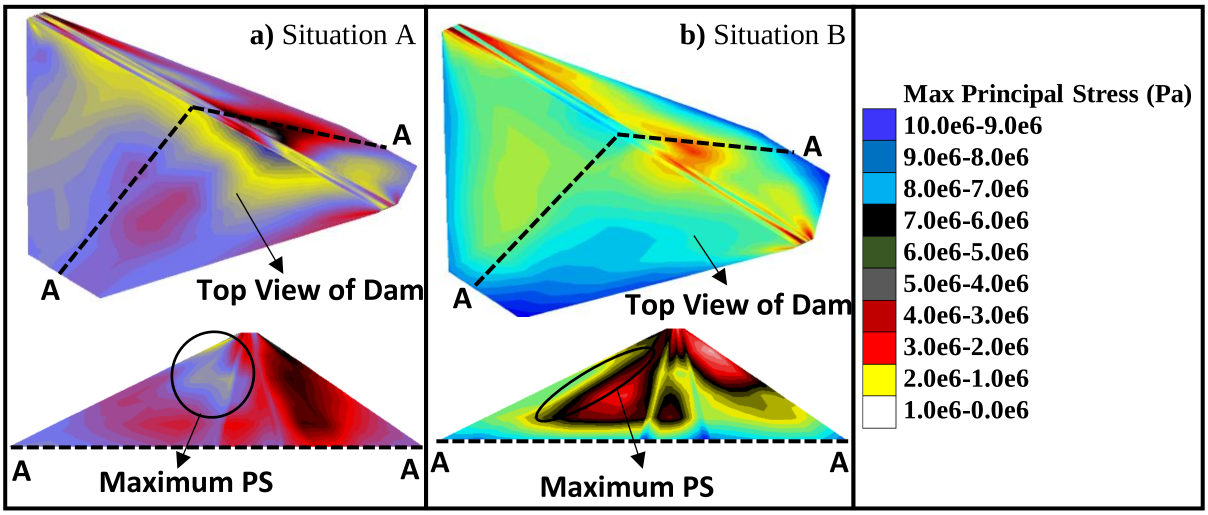


Figure 17. Seismic contours for Situation A and Situation B (Case 9).

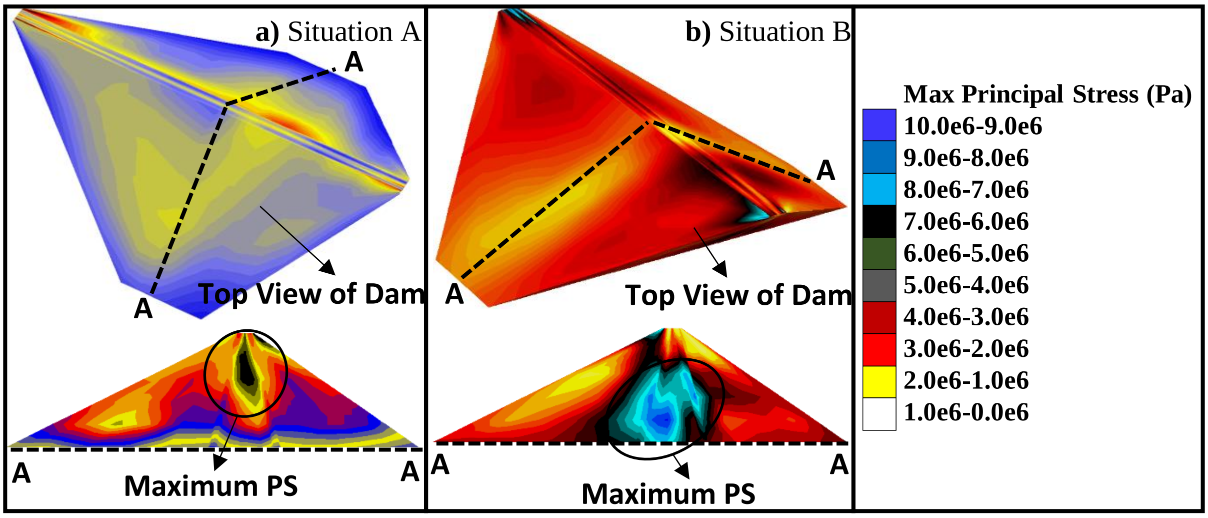


Figure 18. Seismic contours for Situation A and Situation B (Case 10).

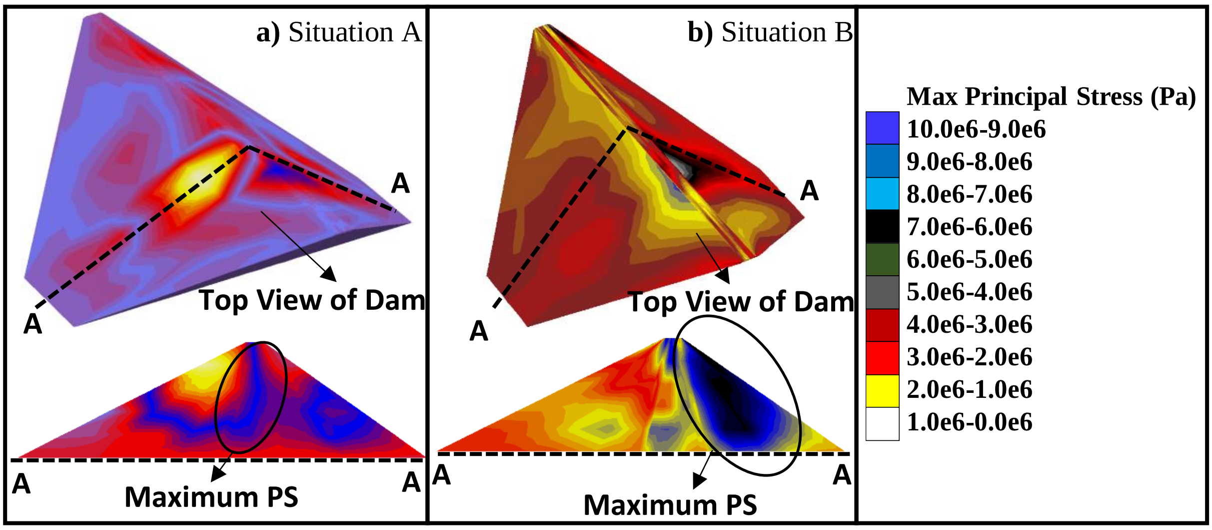


Figure 19. Seismic contours for Situation A and Situation B (Case 11).

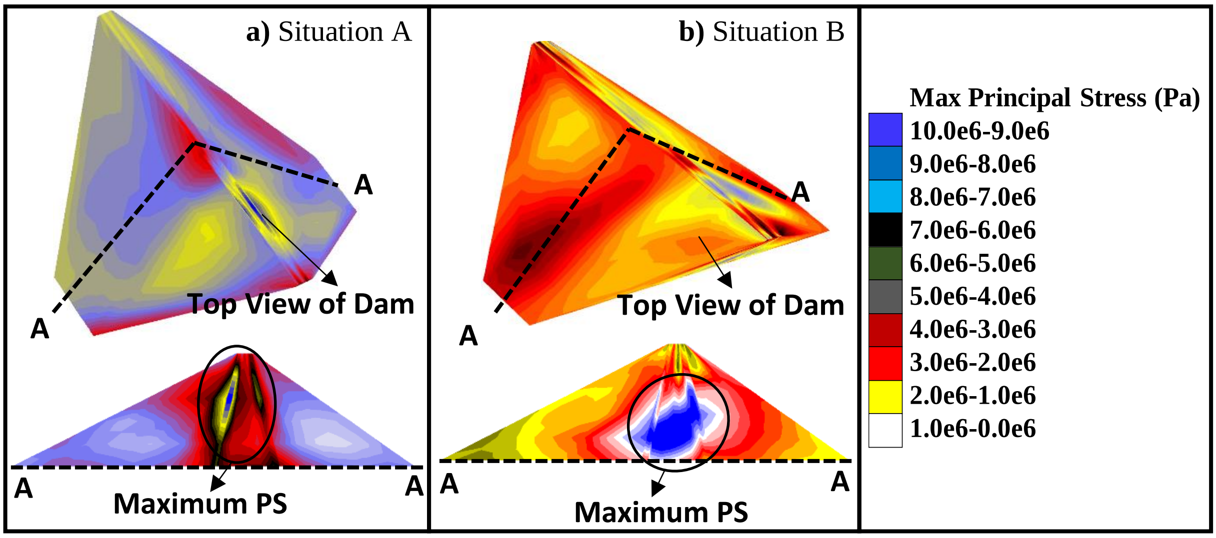


Figure 20. Seismic contours for Situation A and Situation B (Case 12).

In Fig. 17, the seismic PS behavior of the Kozlu dam is examined for Case 9. For Situation A, higher PS values occurred in the upstream parts of the dam body than in the downstream parts. It is concluded that the PS values obtained on the dam body for Situation B are lower than for Situation A (Fig. 17b). For Situation B, approximately 7 MPa PS values are acquired around the clay core and filter materials of the dam. This result shows the importance of clay core and filter materials for the seismic behavior of CCR dams. During the Case 10 earthquake, significant PS values are observed in the clay core material for Situation A (Fig. 18a). For Situation B, approximately 8 MPa PS values are observed at the base of the clay core material of the dam. It is clear from the contour diagrams that the interaction elements between the discrete surfaces of the dam have significantly changed the seismic behavior of the CCR dams. For this reason, as a result of this study, it is recommended that the interaction elements defined between discrete surfaces should not be neglected during the modeling and analysis of CCR dams. In Figs. 19 and 20, the seismic ground motion effects of interaction elements between discrete surfaces on the earthquake behavior of CCR dams are seen in detail. It is concluded that significant PS values occurred around the clay core for both dams, especially during the Düzce earthquake (Case 12) that occurred in 2022 (Fig. 20). Since Düzce province is very close to the Kozlu dam, it is understood that the dam was significantly affected by this earthquake. The seismic displacement results of the Kozlu dam are presented in Figs. 21-32 in detail. Fig. 21 shows the seismic displacement results of the dam for Case 1. For Situation A, the highest displacement values on the dam crest are 19 cm (x direction), 20 cm (y direction), and 32 cm (z-direction). In addition, the highest vertical displacement value observed at the dam crest for Situation B is 21 cm. From this result, the effects of interaction elements on the seismic displacement behavior of CCR dams are seen.

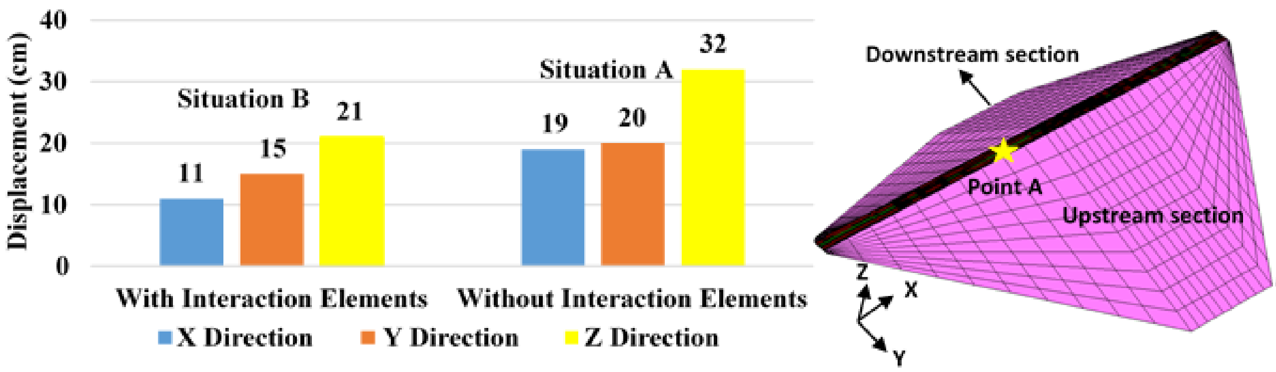


Figure 21. Highest seismic displacement results of Point A for Case 1.

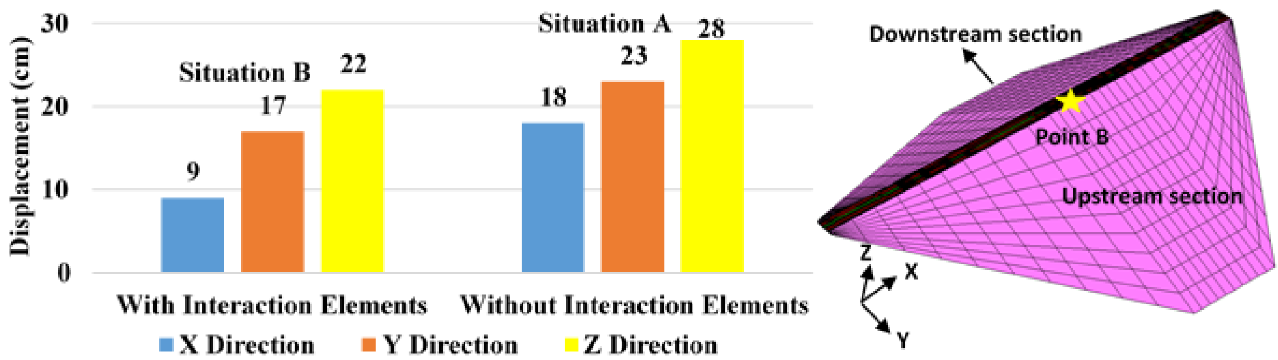


Figure 22. Highest seismic displacement results of Point B for Case 2.

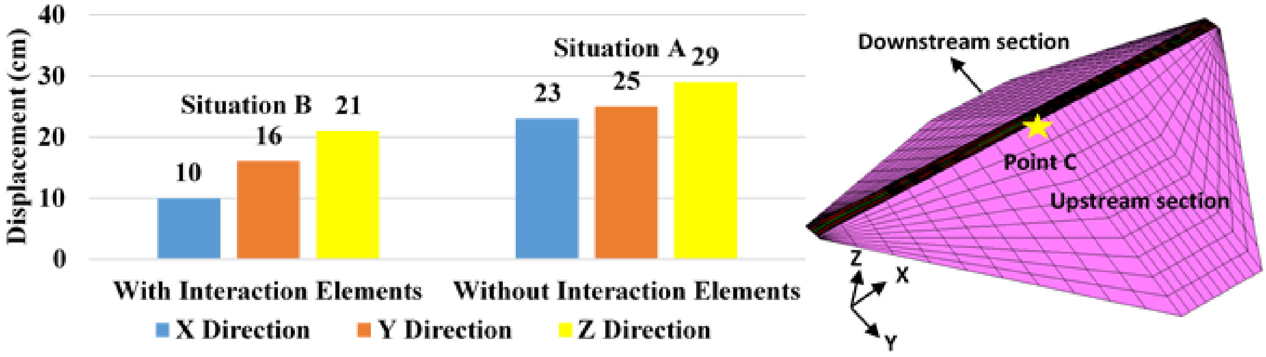


Figure 23. Highest seismic displacement results of Point C for Case 3.

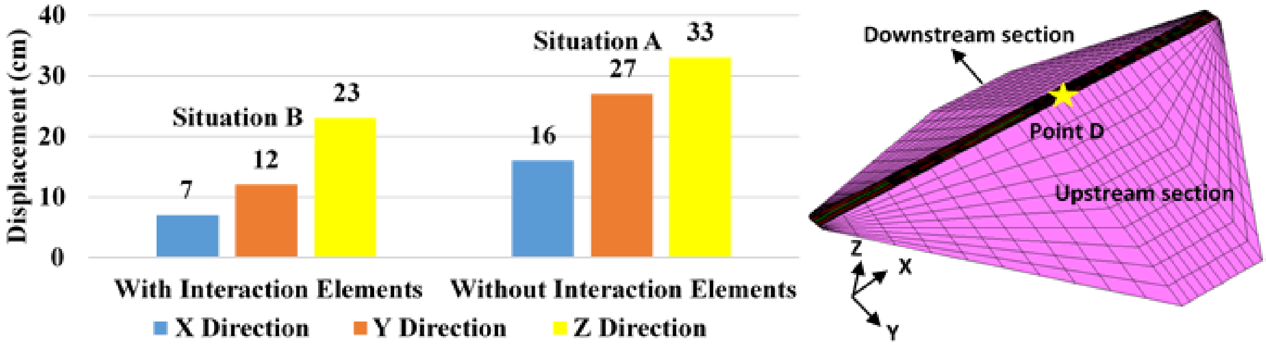


Figure 24. Highest seismic displacement results of Point D for Case 4.

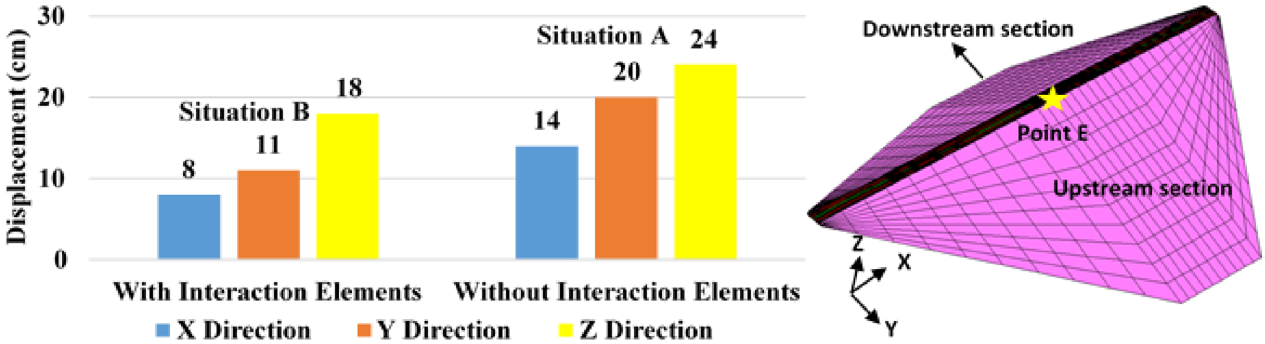


Figure 25. Highest seismic displacement results of Point E for Case 5.

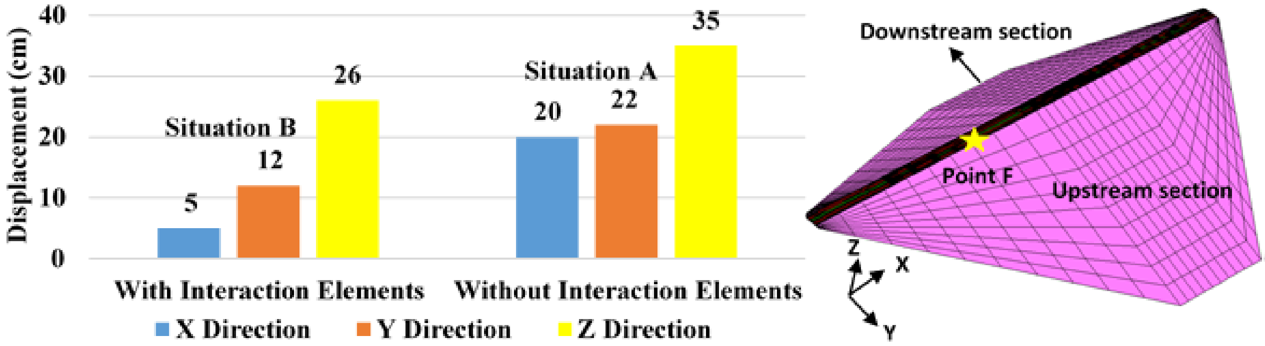


Figure 26. Highest seismic displacement results of Point F for Case 6.

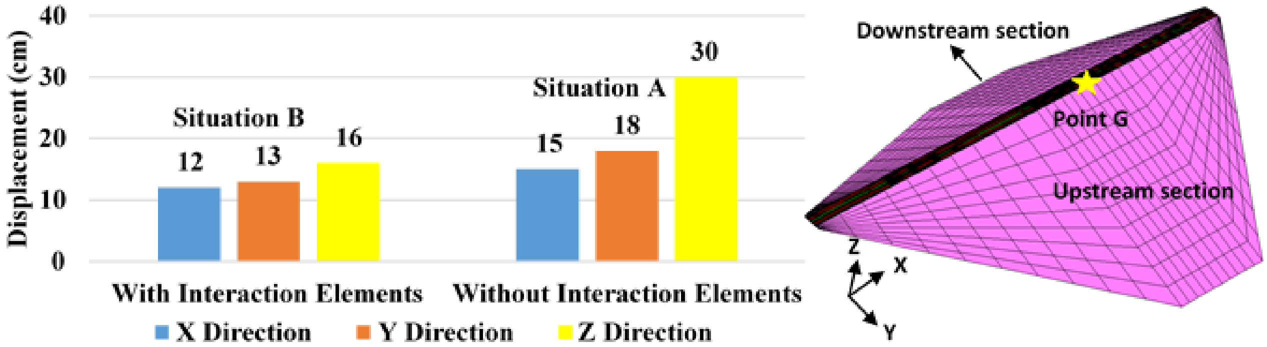


Figure 27. Highest seismic displacement results of Point G for Case 7.

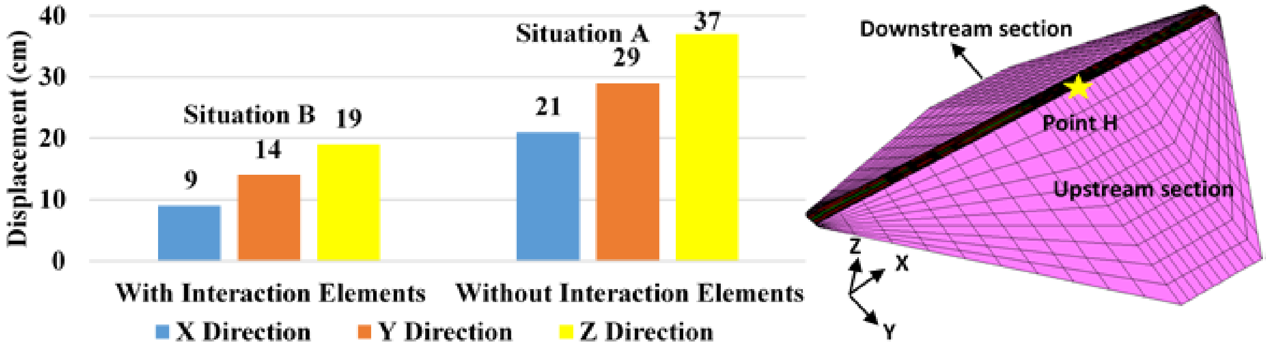


Figure 28. Highest seismic displacement results of Point H for Case 8.

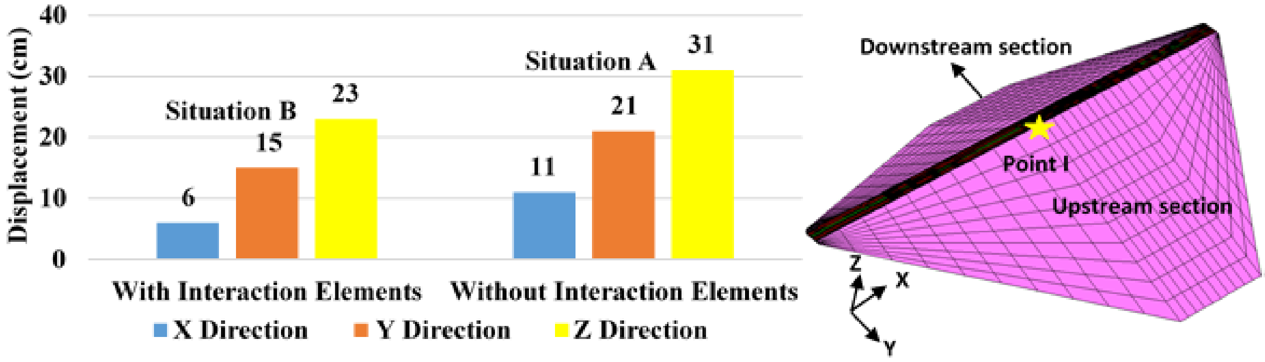


Figure 29. Highest seismic displacement results of Point I for Case 9.

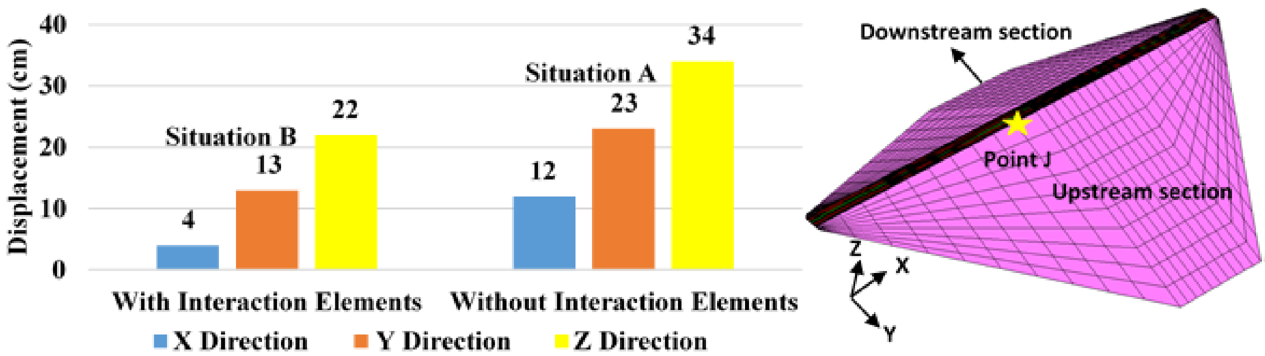


Figure 30. Highest seismic displacement results for Point J Case 10.

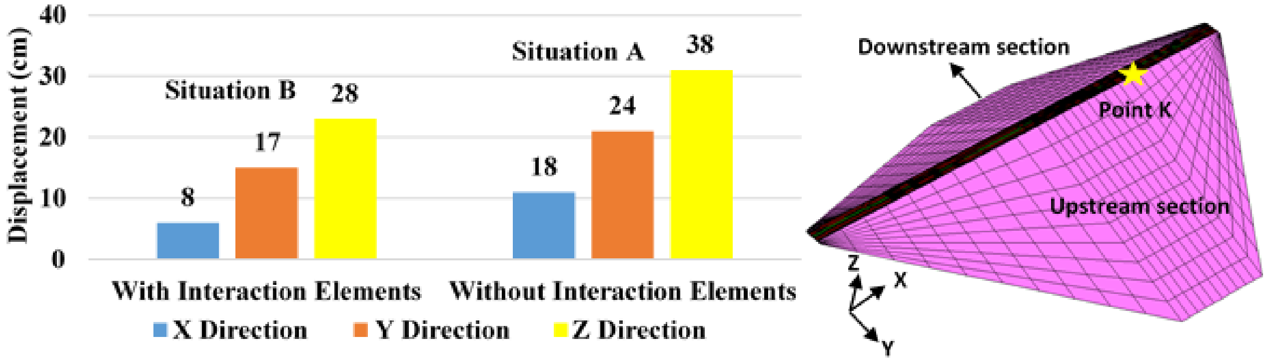


Figure 31. Highest seismic displacement results of Point K for Case 11.

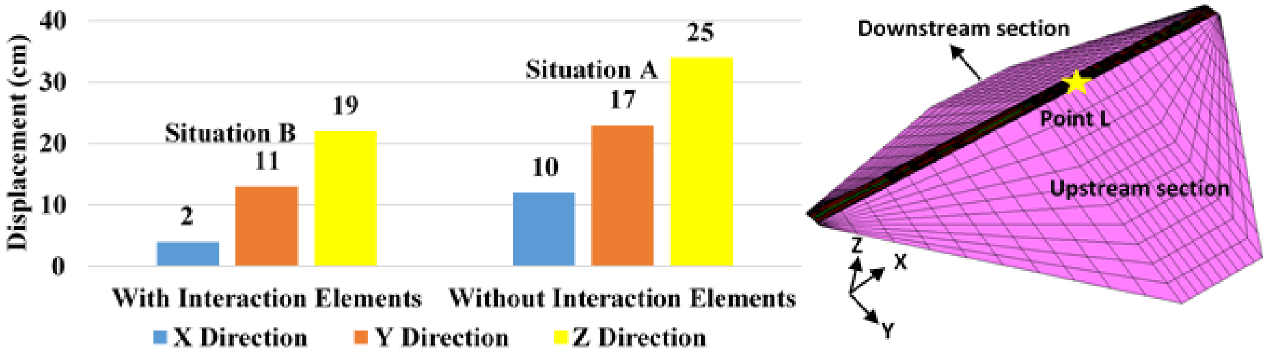


Figure 32. Highest seismic displacement results for Point L Case 12.

In Fig. 22, the seismic displacement behavior of the Kozlu dam is examined for Case 2. For Situation A, the largest displacement values occurring in the x, y, and z directions on the dam crest are 18 cm, 23 cm, and 28 cm, respectively. Moreover, the largest settlement value observed on the dam crest for Situation B is 22 cm. During the Case 3 earthquake, the highest horizontal displacement values acquired on the dam crest for Situation A and Situation B are 25 cm and 16 cm, respectively (Fig. 23). In Fig. 24, the seismic displacement behavior of Kozlu dam is assessed for the Case 4 earthquake. For Situation A, the greatest x, y, and z displacement values on the dam crest are 16 cm, 27 cm, and 33 cm, respectively. Moreover, the largest settlement value for Situation B is 23 cm. During the Case 5 earthquake, the maximum x and y displacements on the dam for Situation A are 14 cm and 20 cm, respectively (Fig. 25). In Fig. 26, the seismic displacement behavior of the Kozlu dam is evaluated for Case 6. The largest settlement values on the dam crest for Situation A and Situation B are 35 cm and 26 cm, respectively. During the Case 7 earthquake, the maximum x, y, and z displacements for Situation A are 15 cm, 18 cm, and 30 cm, respectively. Besides, the highest horizontal displacement value for Situation B is 13 cm (Fig. 27). In Fig. 28, the highest seismic displacement values at the crest of the dam are presented for the Case 8 earthquake. The largest settlement value for Situation A is 37 cm. Furthermore, the maximum x, y, and z displacement values for Situation B are 9 cm, 14 cm, and 19 cm, respectively. During the Case 9, Case 10, Case 11, and Case 12 earthquakes, it is observed that the largest seismic displacement values for Situation A are greater than for Situation B (Figs. 29-32). According to the seismic displacement results, it is concluded that the interaction elements defined between the discrete surfaces of the CCR dams significantly reduce the seismic displacement values occurring on the dam crest.

4. Conclusion and Suggestions

The finite-difference (FD) method-based FLAC3D program offers very important material models and boundary conditions for the investigation of the structural behavior of geotechnical structures. In this study, it is recommended to use the FD method utilized in this study to examine the structural behavior of CCR dams. Besides, the seismic behavior of the Kozlu clay core rockfill (CCR) dam is investigated by considering the body-foundation-reservoir interaction. The 3D model of the dam was created by considering the finite-difference method. Non-reflecting boundary conditions are defined for the lateral boundaries of the dam model. The fix boundary condition is taken into account at the base of the dam model. Special interaction elements are defined between the dam body, foundation, and reservoir water. These interaction elements are assigned between discrete surfaces in the x, y, and z directions. A total of 12 different ground motions are utilized to examine the seismic analyzes of the dam. According to the numerical analysis results, the following important results are acquired.

- It is concluded that the seismic behavior of CCR dams significantly changes when interaction elements are assigned between the discrete surfaces. According to the earthquake analyses, it is observed that the PS and displacement values on the dam body significantly reduce as the interaction elements are defined between the dam body, foundation, and reservoir water. As a result of this study, it is strongly suggested that the definition of interaction elements between discrete surfaces should not be neglected while modeling and analyzing CCR dams.
- The 2022 Düzce-Gölyaka earthquake is of great importance to investigate the earthquake behavior of the Kozlu dam. As a result of the 2022 Düzce-Gölyaka earthquake (Case 12) that occurred in the region close to the Kozlu dam in 2022, the maximum principal stress value occurring on the dam body with interaction elements is 1.3 MPa. Moreover, for Case 12, the greatest principal stress value observed on the dam body without interaction elements is 4.28 MPa. As a result of the Düzce-Gölyaka earthquake analysis, the maximum displacement values on the dam body with interaction elements and the dam body without interaction elements are 19 cm and 25 cm, respectively.
- As a result of the earthquake analyses, it is observed that the seismic PS values on the dam body significantly diminish when the interaction elements are assigned between the discrete surfaces. Moreover, for Situation A (without interaction elements) and Situation B (with interaction elements), the largest PS values occurred around the clay core and filter materials. This result shows that the most critical materials for the PS behavior of CCR dams are the clay core and filter.
- According to the seismic displacement results, it is inferred that the highest displacement values on the dam crest for Situation A (without interaction elements) are greater than for Situation B (with interaction elements). This result shows that the definition of interaction elements in the x, y, and z directions between the discrete surfaces significantly decreases the seismic displacement values taking place in the dam body.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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