The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)

Volume 1, Pages 388-396

ICONTES2017: International Conference on Technology, Engineering and Science

A CASE STUDY ON 3D NON-LINEAR ANALYSIS OF A CLAY CORE ROCKFILL DAM

Ayse Bengu Sunbul
Bulent Ecevit University

Murat Cavusli
Bulent Ecevit University

Murat Emre Kartal
Izmir Demokrasi University

Fatih Sunbul
Ulster University

Abstract: Clay core rockfill (CCR) dams are commonly used and the chosen model dam construction due to their low cost and rapid construction advantages; moreover playing a key role in national water and power management systems. In terms of large water reservoir impoundment behind a high dam, they include a risk to the public, in case of an earthquake, especially for urban areas. Therefore, the stability of dam embankment and analysing seismic safety is of great concern to geotechnical engineers. In fact, these analyses are complex issues which concern both elastic and dynamic effects on the influence of the seismic response to real earthquake records. The objective of this study is to evaluate the three dimensional static and dynamic degrading behaviour of a CCR dam through using the finite difference method. The static part of the analysis considers the layered construction, reservoir impoundment and vertical displacements whereas, the dynamic part considers the response of the dam to a real earthquake recording which represents the typical measures of a peak ground acceleration (PGA) of the study area. Dams should be designed in considering an extreme earthquake with maximum intensity values. In view of this we have investigated the 3D non-linear seismic behaviour of a CCR dam which was subjected to the 1999 Mw 7.1 Duzce earthquake and this is consistent with the idea of an extreme earthquake of about maximum intensity in structural seismic response analysis. The mechanical behavior of the dam material was described using the Mohr–Coulomb failure criterion. Dynamic analyses of the model are performed and the dam behaviour and possible failure phenomena presented. Discussions and comparisons between the non-linear simulation results and existing parameters are expressed.

Keywords: 3D, rockfill dam, earthquake

Introduction

Dams have become a fundamental part of a Nation’s infrastructural body and play an important and beneficial role in the management and development of water in river basins. The use of clay-core rockfill (CCR) dam which is constructed with the optimum use of different geotechnical materials with a permanent clay core, is a preferred model due to its economic reasons. In terms of large water reservoir impoundment behind a high dam, they include risks to the public, especially for urban areas (USCOLD, 1992). In order to assess these risks realistically for both static and dynamic states, finite element (FE) technique and finite difference method (FDM) are the available tools used in the prediction of structural behaviour.

Several researchers have conducted analysis of various types of dams using the FEM. Westergaard (1933) proposed one of the earliest results of the effect of reservoir on the dam based on some assumptions that, water is incompressible; dam is rigid with a vertical face. Fok and Chopra (1985) studied the seismic response of a dam

- Selection and peer-review under responsibility of the Organizing Committee of the conference

*Corresponding author: Ayse Bengu Sunbul-E-mail: absunbul@beun.edu.tr

by means of absorbing boundary conditions. In the review paper by Hall (1988), the importance of both static and dynamic analyses was explained in detail. Later studies have shown the importance of 2D and 3D FEM modelling (e.g. Özkan, Özyazicioglu ve Aksar, 2006; Siyahi and Aslan, 2008a and 2008b; Akkose and Simsek, 2010; Kartal, 2012; Ghaedi et al., 2013). Liu et al. (2016) investigated stress, deformation and settlement analysis of a cut-off wall in a clay core rockfill dam on thick overburden. The results show that selecting plastic concrete with a low modulus can provide high strength of the clay core of the dam and optimize the connection between the cut-off walls which decrease the deformation. Rashidi et al. (2017) evaluated the behavior of rockfill dams during construction and initial impoundment using numerical modeling and instrumentation data. They also recorded 6 years displacement values and those values showed that the most of the settlement took place in dam construction phase compared to the following 6 years period.

Stability is expressed in terms of an overall factor of safety. Progress in the area of geotechnical numerical modelling provide us significant results in the dam physical analysis, in considering complexity such as non-linear behavior modelling, the evolution of the pore pressure during the construction phase and seismic loading under real earthquake data. In fact, the determination of earthquake ground motions is a key issue for the evaluation of the seismic safety of a dam. Seismic ground motions, at a specific dam site, are usually defined in terms of peak ground acceleration (PGA). PGA is the highest intensity of ground motions recorded by the seismograms. Since it is not possible to predict the seismic hazard of a given region, geotechnical engineers consider the maximum intensity in their structural seismic response models.

The paper presents a numerical study of both static and dynamic behaviour of a clay core rockfill dam. All analyses are conducted using a 3D finite difference modelling. Results are presented first considering static analyses including layered constructions, reservoir impoundment and predicted vertical displacements in a selected CCR dam; then analyses are conducted within the framework of non-linearity in vertical displacements in order on evaluate the influence of water reservoir on the seismic response of the dam.

Modellıng

The non-linear analyses which include elasto-plastic (EPNL) and direct non-linear solutions are conducted using the finite difference program FLAC3D. FLAC 3D is a direct finite difference program include constitutive equations, which are elucidated gradually by regular degrees of modelling that allows large strain computations, material anisotropies and other non-linearities. For dam analysis, the Mohr-Coulomb model is applicable as a constitutive step (FLAC3D, 2005). Other models are also implemented into the program’s flowchart by using programming language. At every computing step in the flowchart, incremental strains are calculated in each elementary zone and result in gradual increase of stress derived from the relevant constitutive equations. These steps are followed by an update in zone stress and gridpoint displacements (Roth et al. 1991; Dawson et al. 2001). Seismic loading is applied at the base of the foundation layer as a velocity excitation. The Free-field boundaries procedure in FLAC3D aims absorbing outward waves arise from the structure. FLAC3D contains an optional form of damping, hysteretic damping, that incorporates strain-dependent damping ratio and secant modulus functions, allowing direct comparisons between the equivalent-linear method and the fully non-linear method (FLAC3D, 2005). We followed the same approach in our analysis.

The example model, used in the analyses, is assumed as 35 m in height. The dam has a crest length of 225 m and a crest width of 10 m. It was considered to store 638.000 m^3 of water at maximum capacity (Fig. 1).

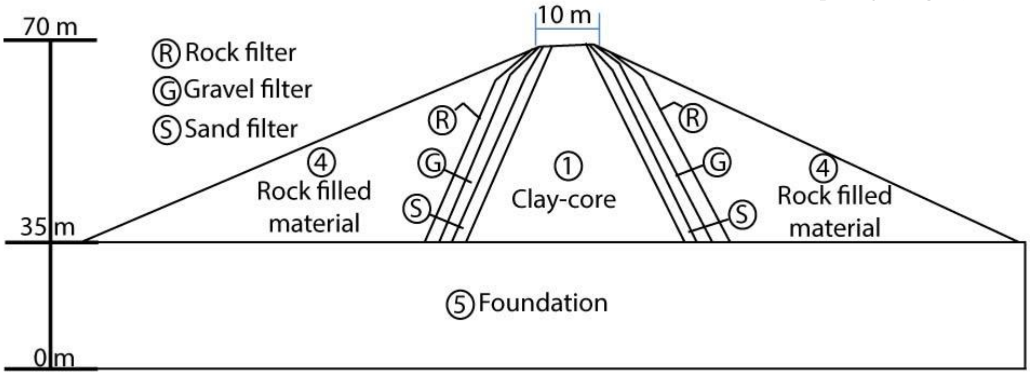

Figure 1. Typical cross-section of the CCR dam used in the study

Numerical methods that have been commonly used to assess the dynamic behaviour of dams mainly include the finite element or finite difference methods-based calculations. In these calculations the non-linear analysis provides the analytical basis of the study which represents the real behaviour of the soil under static (gravitational) and dynamic loadings. In this study, we have used non-linear approach which provides a more complete insight of the behaviour of the clay core rockfill dams and finally contribute to reach the realistic output of the dynamic analysis. The selected material parameters for the dam are shown in Table 1.

Table 1. Foundation and soil properties used in the geotechnical analyses.

Material Properties						
Material	**Maximum Unit Weight**	**Young's modulus**	**Cohesion**	**Internal friction angle**	**Dilation angle**	**Poisson's Ratio**
Clay Core	1.59	21 MPa	50 kPa	26°	0	0.32
Rockfill	1.99	45 MPa	0	37°	8	0.28
Gravel Filter	2.15	32 MPa	0	34°	4	0.30
Sand Filter	2.14	29 MPa	0	32°	3	0.30
Rock Pieces Filter	2.16	34 MPa	0	33°	4	0.29
Foundation	2.25	10 GPa	0	42°	10	0.25

The dam with its foundation (down to 35 m) was modelled by generating brick type zones. The free-field boundaries procedure in FLAC3D is used in order to aim absorbing outward waves arise from the dam structure. Assuming the height of dam as h; we extend the reservoir length up to 3h which is consistent to acquire more realistic results in the seismic response of a dam (e.g. Bayraktar et al., 2012; Kartal et al., 2017). The dam's body is carried out of clay, with slope inclination of 1:2.5 upstream and 1:2.0 downstream. Filter material in both sides of the dam is carried out of rock, gravel and sand, with slope inclination of 1:0.5 (Fig. 2).

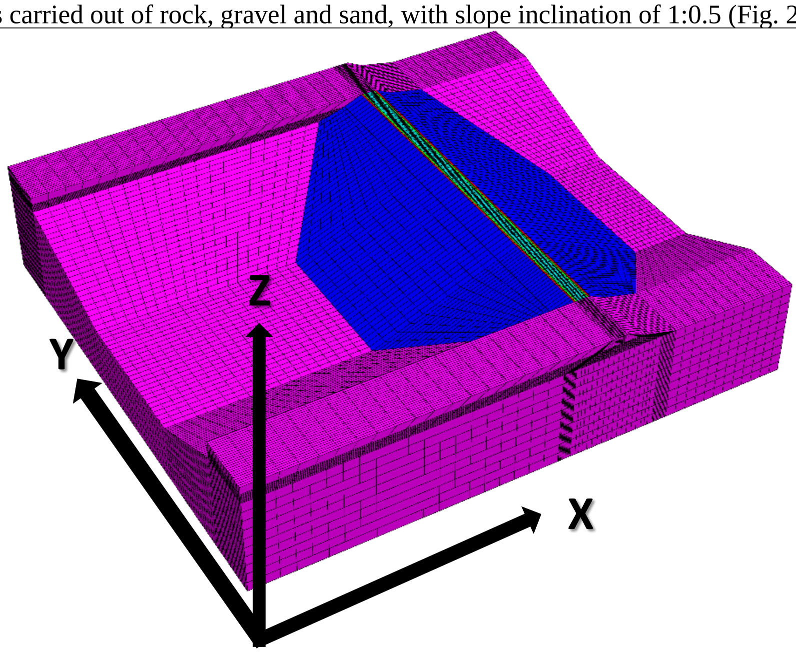

Figure 2. The dam is assumed as having asymmetric zone sections (h: downstream length, 3h: upstream length) with clay core and foundation (See also Table 1 for material properties used in the analysis)

In fact, the two third of Turkey, being located in a 2nd degree earthquake zone according to the Ministry of Public works and Settlement, General Directorate of disaster affairs report (AFAD, 2016). Dams should be designed in considering an extreme earthquake with maximum intensity values. In view of this we have investigated the 3D non-linear seismic behaviour of the CCR dam which was subjected to the 1999 Mw 7.1 Duzce earthquake and this is consistent with the idea of an extreme earthquake of about maximum intensity in structural seismic response analysis. Therefore, we defined the construction area as a 2nd degree earthquake zone in our scenario that, this area has the probability to produce up to 0.4 g peak ground acceleration (PGA) value. Therefore, the example model is subjected to the 1999 Mw 7.1 Duzce Earthquake strong ground motion data which had 0.4 g PGA value (Fig. 3).

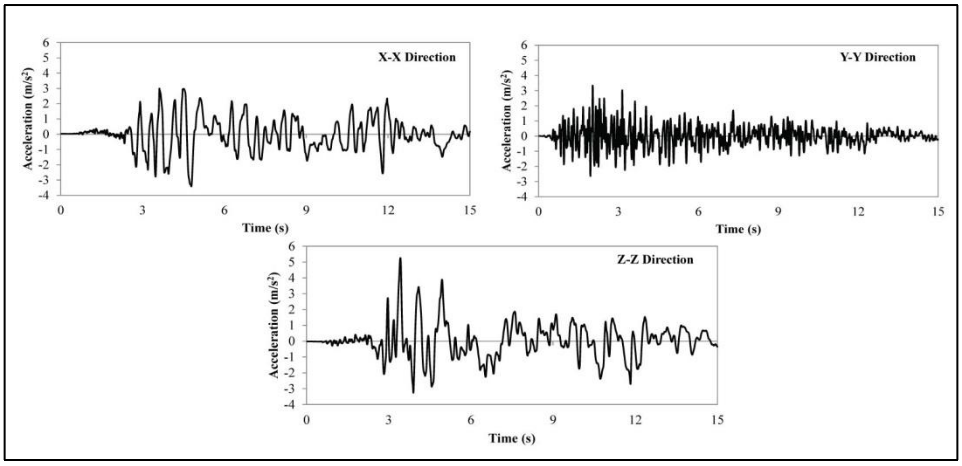

Figure 3. The 1999 Mw 7.1 Duzce earthquake accelerogram

Results

Analyses were conducted in three steps in order to assess the vertical displacements. These steps include static or dynamic analyses of vertical displacements during; a) dam's construction phase, b) full water reservoir phase and c) seismic excitations under real earthquake data. Three observation points (three element integration points: PA, PB and PC), for which the time history graphs of the response quantities are plotted, are marked on the mesh as shown in Fig. 4.

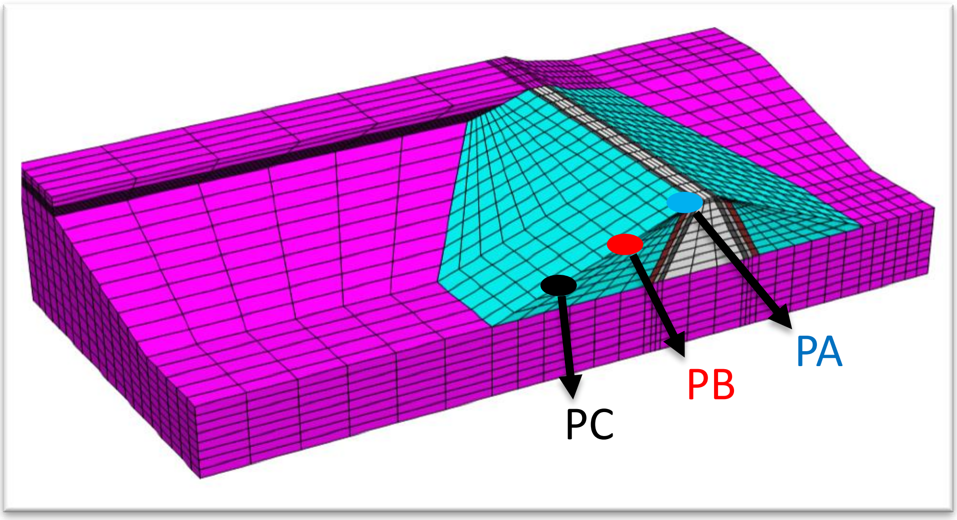

Figure 4. Mesh model presented in a cross-section with three observation points

Construction Phase

The static solutions of the dam empty-reservoir system due to its gravity load are shown in Figure 5. The software has modelled the dam's gravity load in 1500 steps. It is obvious that the maximum predicted displacement values are obtained at the top of the clay core (PA) with the value of 12 cm. The vertical displacements in this phase, are constantly increasing until the 500^{th} step during the analysis. From this point on, the displacements have become constant. When the other two points (PB and PC) in the dam body are examined, the predicted vertical displacement of about 4.5 cm obtained at PB while that value is about 1.5 cm at PC. In general, it was observed that vertical displacement values at the points near the clay core were higher than those at the other points, and vertical displacements decreased as the distance from the clay core increased.

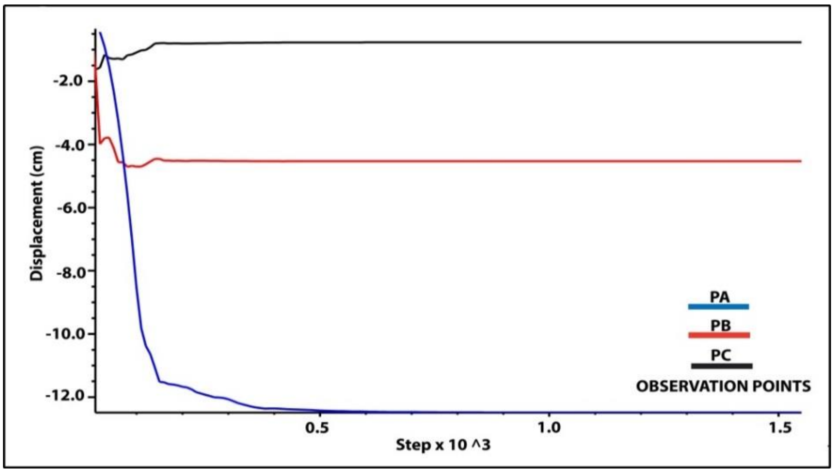

Figure 5. Vertical displacements at PA, PB and PC during construction phase

Figure 6 shows the contour diagram of the vertical displacements values obtained from static analysis in construction phase. It is observed that the maximum displacement value is 21.59 cm in the clay core of the dam. It has been also deduced that the vertical displacement values have decreased according to the direction from core to the outer filter layers, the value reaches down to 5 cm.

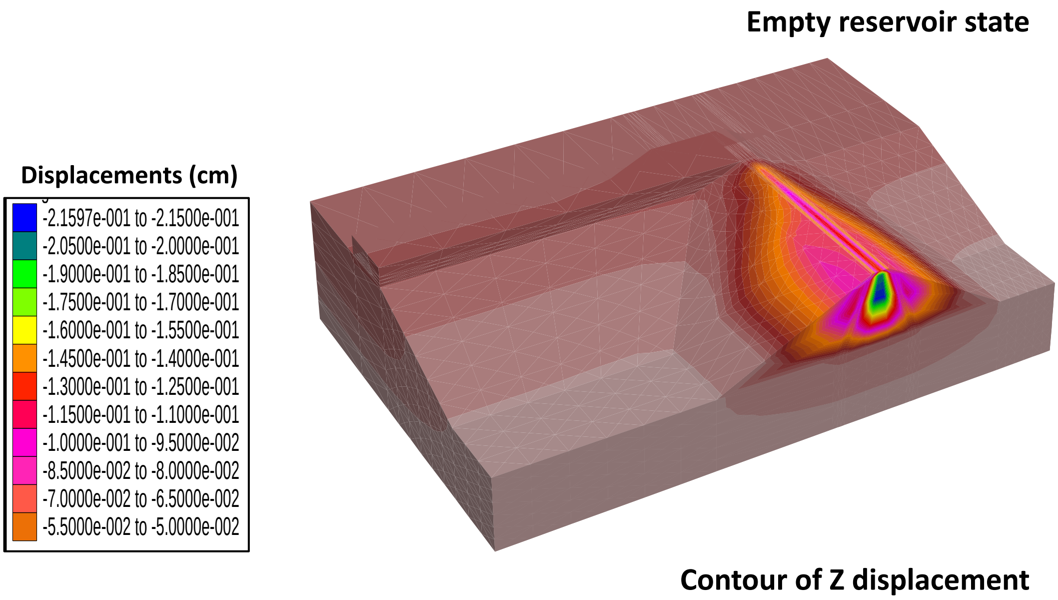

Figure 6. Contour plot of vertical displacements during construction phase

Impounding Phase

The static analyses were also carried out for impounding phase. The reservoir water with an elevation of 35 meters was included in the model using applied pressures to the surface of the reservoir bottom and dam. During impounding, the hydrostatic force acts on the surface of the dam body. It is assumed that the hydrostatic force is zero at the top the dam body. The direction and the magnitude of the hydrostatic forces during the impoundment phase are shown as arrows in Fig. 7.

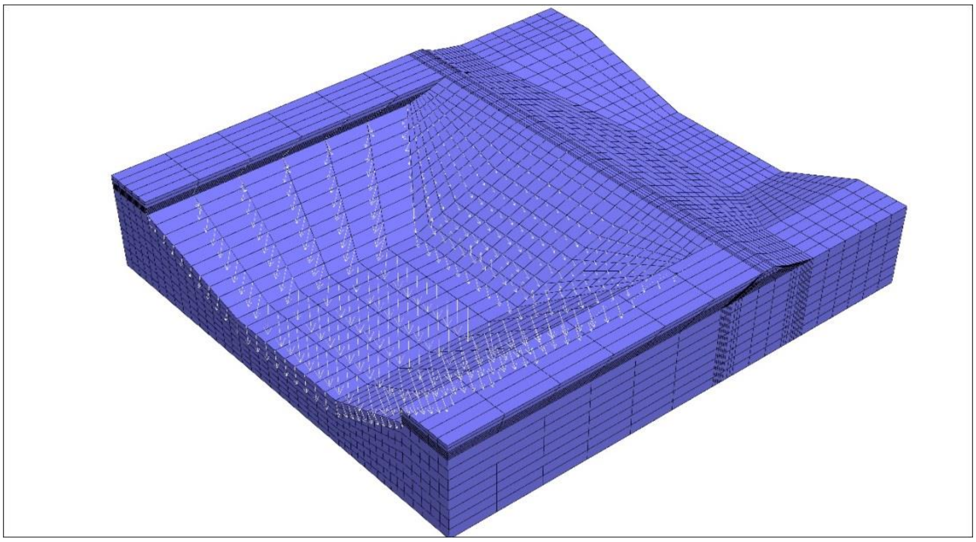

Figure 7. Meshing of the dam model; the hydrostatic force is shown as vectors

Figure 8 shows the non-linear time-history graph of the vertical displacement at PA, PB and PC during full water reservoir phase. The maximum displacement values are observed at the dam's crest up to 18 cm. The vertical displacements obtained at the crest are continuously increasing up to 500th step and the value become more stable after that point. At PB and PC, vertical displacements of 11.5 cm and 6.5 cm were calculated, respectively. According to the predicted data, the largest displacement occurred in the clay core, which is the weakest material of the dam body. Moreover, when the empty state and the full water state of the dam are compared, it has been observed that the vertical displacement values occurring at the crest point of the dam increase depending on the reservoir water. Furthermore, after starting impounding stage, it was observed that the vertical displacements were visibly increased due to the hydrostatic pressure acting on the points B and C.

The influence of the variation of the water level in the reservoir is also compared. In both cases (empty and full water reservoir states), we obtain higher displacement variations at PA when compared to PB and PC.

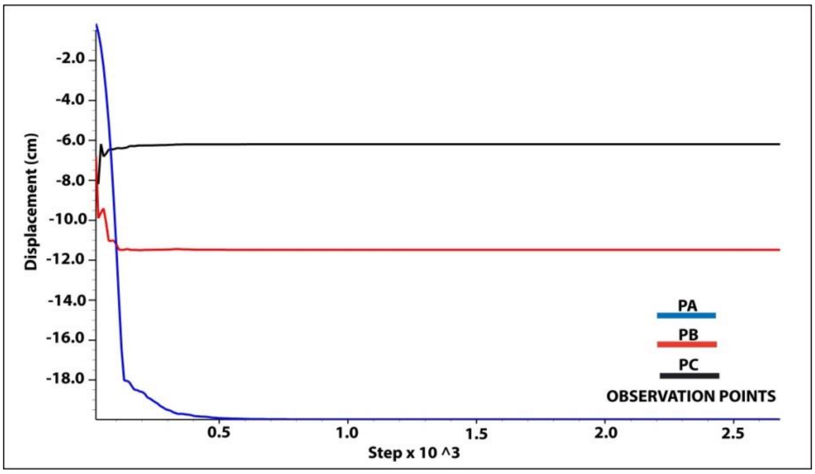

Figure 8. Vertical displacements at PA, PB and PC during impounding phase

Figure 9 shows the contour diagram of vertical displacements obtained at the dam's body during the impoundment phase. The maximum vertical displacement occurs at dam clay core with magnitude 41 cm. In terms of displacement values over the filter layers; we obtained displacement with magnitude 17 cm due to hydrostatic pressure. This value is higher than those obtained in the empty reservoir phase. The results are in good agreement with previous studies (Parish, 2007).

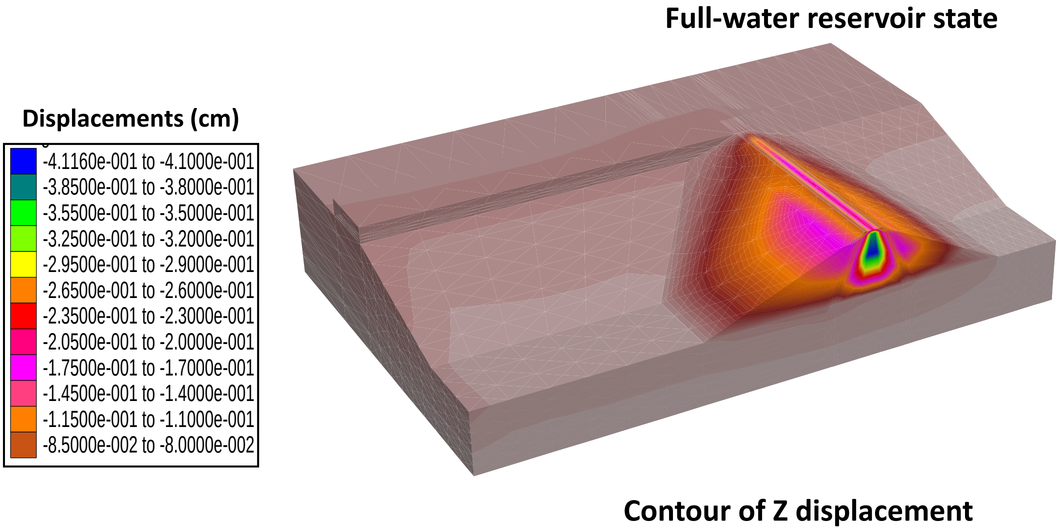

Figure 9. Contour plot of vertical displacements during the impounding phase

Dynamic Phase

Fig. 10 shows the vertical displacement time history of the dam under seismic loading for 15 sec. The maximum displacement occurs at dam crest (PA) with magnitude 86 cm. Those values decrease down to 45 cm at PA and PB. The peak values are observed in the strong ground motion record in the first 5 sec period. After that time period, we observe continuous displacement values where the residual deformations are being estimated. The higher predicted displacements are also observed at PC when compared to PB.

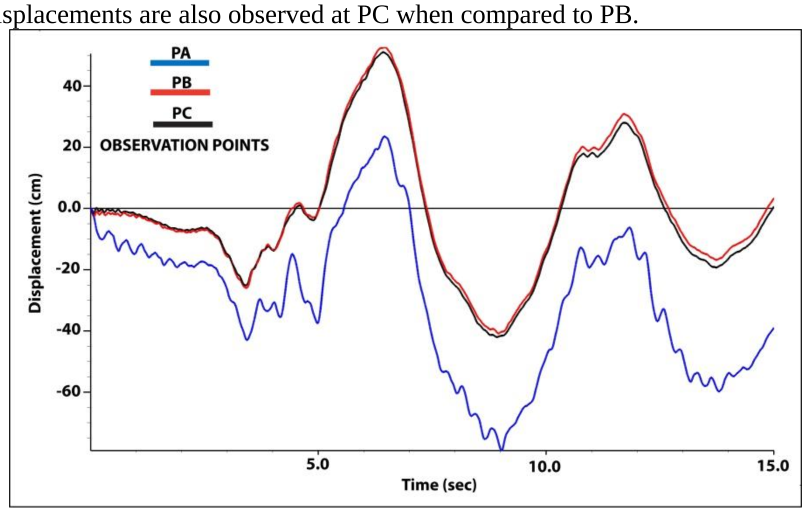

Figure 10. Vertical displacements at PA, PB and PC during seismic excitation phase

Fig. 11 shows the dynamic response of the dam under earthquake loading. From Fig 11, displacement responses increase gradually from bottom to top and displacement response of dam crest are larger than those observed at the dam foot.

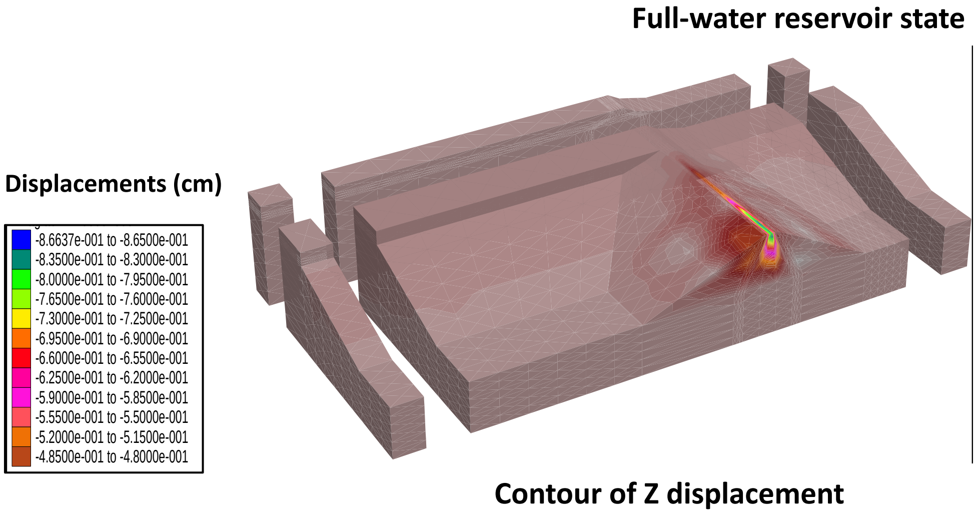

Figure 11. Contour plot of vertical displacements during seismic excitation phase

Conclusion

In order to assess static and dynamic vertical displacements on a selected CCR dam, three dimensional non-linear analyses were carried out. The static part of the analysis considers the vertical displacement variations following construction phase and reservoir impoundment whereas; the dynamic part considers the response of the dam to a real earthquake recording. The results of this study are summarized as follows;

- During the construction phase (static state); the maximum displacements were observed at the top of the clay core (crest of the dam). The predicted displacement value was 12 cm at the crest, whereas this value was gradually decreased in consideration of lower parts of the dam body. The 3D contour diagram also shows that the displacement value obtained in the clay core was approximately 21.5 cm.

- During the impounding phase (static state); the predicted vertical displacement value observed at the dam crest was 18 cm and gradually increased towards to the bottom level. The 3D contour diagram for this case shows the maximum displacement value with magnitude 41 cm at dam clay core.

- The static state analyses show a gradual increase in the magnitude of vertical displacements during an impounding stage where the hydrostatic force acts on the surface of the dam body and causes additional force on the clay core section.

- During the dynamic phase; the CCR dam was subjected to the ground acceleration histories obtained by the 1999 Mw 7.1 Duzce earthquake which had 0.4 g peak acceleration value. The seismic excitation increased the magnitude of displacements when compared to the static phases. We observe 86 cm vertical displacement value at the crest of the dam in the first 5 sec of recording. For the rest of seismic excitement, the residual/permanent deformations have been also observed due to the continuous seismic loading.

References

AFAD, (2016), Disaster and Emergency Management Authority, Earthquake department catalogue, 2007-2016. http://www.deprem.gov.tr.

Akköse, M. and Şimşek, E. (2010), “Non-Linear Seismic Response of Concrete Gravity Dams To Near-Fault Ground Motions Including Dam Water-Sediment-Foundation Interaction”, Applied Mathematical Modelling, 34, No. 11, pp. 3685-3700.

Bayraktar A. et al., (2012), “Comparison of Near-Fault And Far-Fault Ground Motion Effects On Geometrically Nonlinear Earthquake Behavior of Suspension Bridges”, Natural Hazards, Volume 64, Issue 1, pp 593–614.

Dawson,E.M., et.al.,(2005), “A Practice-Oriented Pore Pressure Generation Model”, Proc,2nd Inter. FLAC Symposium, France Itasca Consulting Group, Minnesota 55401 USA.

FLAC3D, Itasca Consulting Group, FLAC: (2005), Fast Lagrangian Analysis of Continua, vol. I. User's Manual, vol. II. Verification Problems and Example Applications, Second Edition (FLAC3D Version 3.0), Minneapolis, Minnesota 55401 USA.

Fok K.L. and Chopra A.K.,(1985), "Earthquake analysis and response of concrete arch dams", Earthquake Engineering Research Center. Report no. UCB/EERC-85/07. University of California Berkeley, California; 151p.

Ghaedi K., Mohammed Jameel, Zainah Ibrahim (2015), "Seismic Analysis of Roller Compacted Concrete (RCC) Dams Considering Effect of Sizes and Shapes of Galleries", https://www.researchgate.net/publication/276834342.

Hall J. F. (1988), "The dynamic and earthquake behaviour of concrete dams: review of experimental behaviour and observational evidence", Soil Dynamics and Earthquake Engineering,7, Issue 2, Pages 58–121.

Kartal M. E. (2012), "Three-dimensional earthquake analysis of roller-compacted concrete dams", Natural Hazards and Earth System Sciences, 12(7); 2369-2388.

Kartal, M. E., Cavusli, M. and Sunbul, A. B (2017), "Assessing seismic response of a 2D roller-compacted concrete dam under variable reservoir lengths", Journal of Earthquake and Structures, (in press).

Liu L et.al., (2016), "Numerical stress-deformation analysis of cut-off wall in clay-core rockfill dam on thick overburden", Water Science and Engineering Vol.9, Issue 3, Pages 219-226.

Özkan M, Özyazicioglu M, Aksar U D. (2006), "An evaluation of Güldürcek dam response during 6 June 2000 Orta earthquake", Soil Dynamics and Earthquake Engineering, 26(5): 405–419.

Parish Y., (2007), "Numerical analysis of the seismic behaviour of earth dams: influence of plasticity and pore water pressure", PhD Thesis, University of Science and Technology of Lille, France.

Rashidi M., Haeri S.M. (2017), "Evaluation of behaviors of earth and rockfill dams during construction and initial impounding using instrumentation data and numerical modelling", Journal of Rock Mechanics and Geotechnical Engineering 9.

Roth et.all. (1991), "A moving grid method applied to one-dimensional non-stationary flame propagation". Int. Journal of Numerical Methods in Fluids, vol. 13, Issue 7,Pages 869–882.

Siyahi B, Arslan H. (2008a), "Non-linear dynamic finite element simulation of Alibey earth dam", Environmental Geology (Berlin), 54(1): 77–85.

Siyahi B, Arslan H. (2008b), "Earthquake induced deformation of earth dams", Bulletin of Engineering Geology and the Environment, 67(3): 397–403.

USCOLD (US Committee on Large Dams). (1992), Observed Performance of Dams during Earthquakes. Committee on Earthquakes, Denver, CO.

Westergaard, H.M.,(1933), Water pressures on dams during earthquakes. Am Soc Civ Eng Trans, 98(2); 418-433.