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Investigation of Three-Dimensional Nonlinear Behaviour of Atatürk Dam

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Abstract:

One of the most important reasons for the damage in clay core rockfill (CCR) dams is the sudden and big settlements of these dams. Therefore, it can be indicated that the forecast of sudden settlement in a clay core rockfill dam is extremely important. In the present study, it is presented that how the behavior of this type of dams changes by effect of the reservoir water according to the numerical analyses. Atatürk dam, which is the biggest clay core rockfill dam built in Turkey, was selected in three-dimensional analyses. Three-dimensional finite element model of Atatürk dam was modelled using FLAC3D software which is based on the finite difference method. Mohr-Coulomb material model was used for clay core, filters, rockfill and foundation in nonlinear analyses. Numerical analyses were carried out for empty and full reservoir water condition of the dam. Thereby the effect of reservoir water on the non-linear behaviour of the CCR dam is assessed after finite element analyses. According to the numerical analyses, it was observed that how much vertical settlement on crest of the Atatürk dam will occur. Based on the numerical analyses, when compared empty and full reservoir conditions of the dam, significant differences in vertical displacement were observed in the clay core and on the dam body.

Key words: Clay core rockfill dam, Mohr Coulomb material model, Finite element model, Settlement behavior.

1. Introduction

Since the water need increases with industrial and agricultural requirements, the number of new water supplies, including dams, increases proportionally. In near future, the current infrastructure probably would not supply adequate water demand in many regions around the world. Insufficient city infrastructures, which cannot provide the people needs, can lead to risk of human life. There are several options to provide the additional water resources; one of the them is the construction a dam [1]. Dams, including rockfill zones, are one of the most important structures for providing water for humans in terms of human sustainability. The types of conventional rockfill dams are; clay core rockfill dams, concrete-faced or asphalt-faced rockfill dams. In recent years, these immense constructions have great interest due to the increase in rise of environmental awareness and renewable energy. A clay core rockfill (CCR) dam was constructed with an optimum use of different geotechnical materials and these dams have a clay core in their center. CCR dams are built for many purposes such as irrigation, energy production and flood control. Also, these dams are preferred for their economic advantages and easy construction. Generally, these structures are constructed in valleys where there are sufficient amount of rock materials and the foundation rocks have favorable quality. According to the world's leading engineering and economical researches, a rockfill dam with impervious clay core is the best choice for the ultimate design [2].
A clay core rockfill dam should be able to resist all static and dynamic effects that have been loaded

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onto its lifetime. Generally, there are two different types of deformations associated with CCR dams. The first one is the vertical displacements occurring from the dam's own weight. The second one is the horizontal deformation which is perpendicular to the main axis of the dam. Settlement is one of the most important deformation characteristics of a high clay core rockfill dam. It is regarded as a key indicator of dam safety. Investigation of dam behavior under reservoir loads may be vital for CCR dams. Many researchers investigated the settlements of rockfill dams in previous decades. Kovacevic et al. [3] and Duncan [4] are the most important contributors to developments in numerical analyses of embankment deformation behaviors, mainly for zoned earth and rockfill dams. Justo [5] and Naylor [6] suggested many methods for the incorporation of collapse settlement of rockfill into constitutive models. Cetin et al. [7] investigated vertical settlements in the Atatürk Dam, which is the biggest rockfill dam in Turkey. After the dam started to reserve water, settlements appeared at the crest of the dam. Vertical settlements were also observed in the dam during the following five years. They observed that vertical settlements increase at crest of dam as time progresses. Zhan et al. [8] performed time dependent deformation analysis in the high rockfill dam. Deformations were observed by numerical simulation and in geodetic measurement. They compared both results graphically and numerical analyses were confirmed using geodetic measurements. Yu et al. [9] performed a parametric study on stability of rockfill dams. They performed 2D and 3D numerical analyses and they examined behaviour of rockfill dam. Zhang and Zhang [10] modelled a three-dimensional rockfill dam and performed numerical analyses under different conditions; including dam construction, water storage and effect of earthquake. According to the results, they evaluated displacements and stresses which were obtained from numerical analyses. Fang and Liu [11] investigated two dimensional analyses of the rockfill dam. They investigated the deformations and principal stresses of the rockfill dam after the construction and under the normal water depth condition. Zhou et al. [12] examined vertical settlements in a rockfill dam under different conditions. These settlements were obtained from numerical calculations and geodetic observations. The time-dependent settlement behaviour of a rockfill dam was investigated on the basis of settlement-monitoring records and displacement back analysis. In addition, numerical analyses were verified with geodetic measurement results. Xu et al. [13] modelled three-dimensional finite element model to perform numerical analyses and they investigated nonlinear behaviour of the rockfill dam. The model parameters were calibrated by triaxial tests. The step-by-step construction followed by subsequent impounding of the reservoir water was simulated in the numerical procedure. The numerical results agree well with in situ monitoring records of dam settlements. Kartal et al. [14] investigated the rockfill dam under static loads using the improved Rackwitz-Fiessler method. Numerical analyses were performed considering the self-weight of the dam and the hydrostatic pressure of the reservoir water. Kim et al. [15] investigated the deformation characteristics of a rockfill dam during the dam's construction and initial reservoir filling phases. Two-dimensional finite element analyses were performed to assess the displacements during both the construction and initial reservoir filling stages. In addition, geodetic measurement results of the rockfill dam were shown in this study. Observed displacement results and numerical analyses are similar and numerical analyses were confirmed by measurement results. Prampthawee et al. [16] performed the time-dependent analyses of high rockfill dam. Three-dimensional finite element analyses without creep and with creep considerations of rockfill dam have been compared with the situ measurements. Besides, numerical analyses were verified by measurement results. Wen et al. [17] evaluated measurement results which were obtained from a detailed deformation-monitoring system and three dimensional numerical analyses and measurements were compared and confirmed

with numerical analyses.
In this study, we investigated the non-linear behaviour of Atatürk Dam, which is the largest clay core rockfill dam in Turkey and located between the cities of Sanliurfa and Adiyaman. The three-dimensional dam-reservoir-foundation interaction system of Atatürk dam was modelled by the finite difference method using FLAC3D software. Finite difference method is used in numerical solutions. Mohr-Coulomb material model was used for dam body (clay core, alluvium, rockfill materials and filter zones) foundation in all non-linear analyses. As the first step of numerical analyses, only the foundation was considered and it was collapsed under its self-weight. Then, the dam body was placed on the settled foundation model. After the foundation-dam body system was collapsed under its self-weight, reservoir water loads were performed on the dam body and reservoir-dam body-foundation system was modelled. Afterwards, the Atatürk Dam was analyzed for empty reservoir water condition and 170 m (full reservoir condition) of the reservoir water depth. Vertical displacements were evaluated for two different reservoir conditions. The results showed that the occurrence of reservoir water increases the vertical displacements in the dam body obviously. Moreover, it is clearly seen that significant displacement differences occurred when increase reservoir water level. When the reservoir water is considered approximately 2 m vertical displacement differences occurred at the dam body.

2. Atatürk Dam

The Atatürk Dam which is a clay core rockfill dam, was constructed between the Sanliurfa and Adiyaman provinces in South-East of Turkey (Fig. 1). The dam is one of the largest rockfill dams built in the world. It was constructed under the South-Eastern Anatolian Project. The project includes 22 dams, 19 hydroelectric plants, 26.5 km long irrigation tunnels with 25 ft in diameter and thousands of miles of irrigation canals to irrigate 1.800.000 ha of land. The height of the Ataturk Dam is 169 m.

Figure 1. The location and view of Atatürk Dam.

Its crest length is 1664 m and the crest width is 15 m. Maximum and minimum water depths of dam are 542 m and 526 m, respectively. Moreover, maximum and minimum reservoir volumes are

48.7 km^3 and 29.4 km^3, respectively. The reservoir area of Atatürk Dam is 817 km^2. The dam has 8 different turbines to generate energy and it generates 8900 GWh of energy annually. The fill of the dam contains a high plasticity clay slaking and associated sliding problems for the impervious zone, natural and processed alluvium for the filter zones, basalt and plicated limestone for the shell zones. In contrast to the estimated construction period (5-5.5 years), all processes for building the dam ended in exactly 3 years and 8 months (Cetin et al. 2000). The typical cross section of Atatürk dam is demonstrated in Fig. 2. The dam body has oval dam geometry and this situation caused many problems during finite difference modelling. In addition, the oval geometry has double curvature. The slope of the upstream is 1:2.15 and slope of the downstream is 1:2.2. Slopes of core wall, filter, zones and transition zones are 1:45. Atatürk dam has different filling materials in the body and these materials have 9 different mechanical properties. The most critical section of Atatürk Dam is shown in Fig. 2.

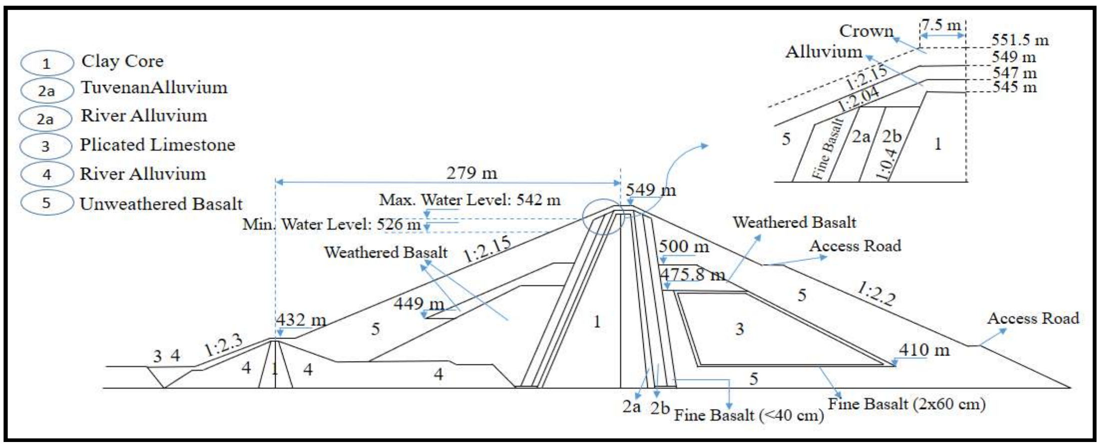

Figure 2. Typical cross section of Atatürk Clay Core Rockfill Dam [18].

The dam was built as central clay core rock fill dam. There are various materials around the core such as basalt, alluvium etc. A high plasticity type clay was used in the construction of the clay core. Moreover, while constructing the clay core, clay was laid in 0.3 m thick lifts and compacted by sheepsfoot rollers. Properties of the materials were selected from the experimental studies and literature as given in Table 1.

Table 1. Material properties of Atatürk Dam body [18].

Characteristics	*Specific Weight*	*Maximum Unit Weight*	*Porosity*	*Water Content*	*Air Content*	*Material Content*
Unit	g/cm^3	g/cm^3	%	%	%	%
Clay	2.67	1.59	40.45	24.50	15.95	59.55
Filter 2A	2.72	2.09	23.16	5.59	17.57	76.84
Filter 2B	2.74	2.10	23.36	1.38	21.98	76.64
River Alluvium	2.74	2.23	18.61	4.05	14.56	81.39
Plicated Limestone	2.68	1.99	25.75	7.78	17.97	74.25
Basalt	3.01	2.25	25.25	1.50	23.75	74.75

3. Three-dimensional finite difference model

Deformation monitoring at all stages in a dam's life is very significant for safety and the future of the clay core rockfill dam. For this reason, based on the usage of FLAC3D software, a three-dimensional (3D) finite difference model of the Atatürk Dam was modelled and deformations in the dam body were observed. The 3D model was created according to the original dam geometry. Since the Atatürk dam has oval double curvature geometry, the finite difference model was created accordingly. The 3D model of dam body has 9 different sections. These have 9 different geometrical properties. 9 various sections create 8 different blocks in the finite difference model (Fig. 3). Creating three dimensional models and meshing this 3D model were time consuming and hard processes. Thus, the work took great effort and many weeks. The model was constructed exactly the same as in the original dam project. After the three dimensional model of dam body was constituted, the foundation was modelled in detail. The foundation model was extended toward downstream and the valley side as much as dam height. Also, it was extended three times of the dam height at upstream side of dam [14]. Finally, foundation height was considered as much as the dam height (Fig. 4). In total, 10 different materials were used in the dam body-reservoir-foundation system.

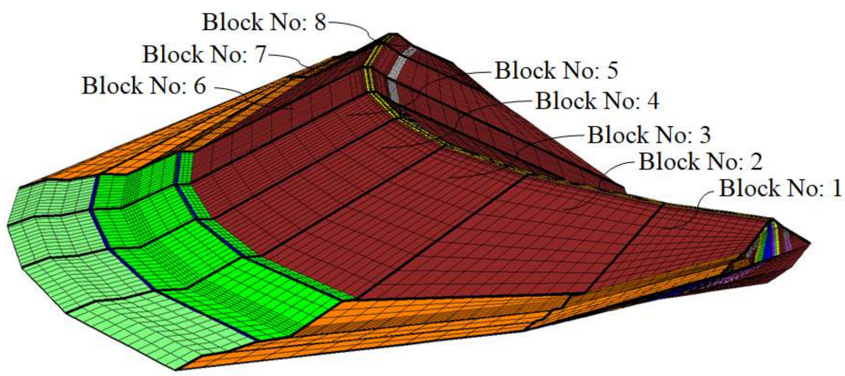

Fig. 3. Three dimensional models of Atatürk Dam body.

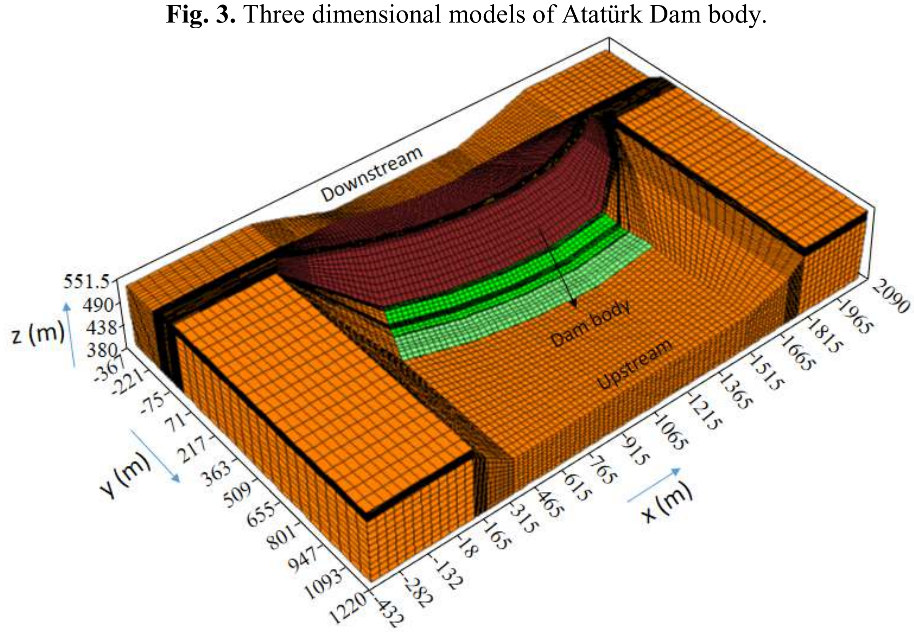

Fig. 4. Three-dimensional model of Atatürk Dam-Foundation interaction system.

2 various cases of the three dimensional non-linear analyses are presented below. These cases are shown in Table 2.

Table 2. Two different cases for numerical analyses.

Case	Reservoir Height
Case 1	Empty Reservoir
Case 2	Full Reservoir (170)

When focusing on the Table 2, numerical analyses were observed for 2 different reservoir conditions. Different 3D models were created for 2 situations. Before performing the numerical analyses, the 3D finite different model of the Atatürk dam was created for empty reservoir condition. Then, as in the original dam project, materials properties were defined for each volume. The movement of the base of foundation was restricted in three directions (x, y, z). Moreover, the movement of the side surfaces of the model was allowed only in the vertical direction (z) and it was restricted in the horizontal directions (x, y). Mohr-Coulomb material model was defined for dam body and foundation. Firstly, numerical analysis was completed only for empty reservoir condition. Prior to the filling of reservoir, the foundation was collapsed under its own weight. Then, the dam body was placed on the settled foundation model and this 3D finite difference model was collapsed in the Case 1. Afterward, all displacements which were obtained from the collapsed model were set to zero. This was achieved in order to exclude construction related deformations and obtain accurate displacement created by the first analysis. Then the reservoir was filled up for 170 m (full reservoir) of reservoir water depth and the reservoir-dam-foundation system was modelled. This is not automated process and therefore each process was calculated individually.

3. Numerical results and discussion

Three dimensional nonlinear analyses of the clay core rockfill dam are presented in detail in this section. Vertical displacements are presented graphically for 2 different reservoir conditions and these numerical results were compared with to each other. According to numerical analyses nonlinear behaviour of the dam was evaluated.

3.1. Vertical displacements for empty reservoir condition

According to nonlinear numerical analyses, vertical displacements of the CCR dam for empty reservoir condition of the Atatürk dam are presented in Fig. 5-6. 3 nodal points were determined on the dam body so as to see better the vertical displacements in the dam when the water is taken into account. The vertical displacements in these three nodal points are shown graphically in this section. In addition, the dam was divided into two parts from the midpoint of the center to examine the behavior changes in the dam body in detail. Because of the dam body was not exposed to any external force for empty reservoir condition of the dam, the vertical displacements occurred only at the dam body and around the clay core. In addition, the maximum settlements took place in the clay core. The maximum vertical displacement occurred in clay core is 3.42 m (Fig. 5). Moreover, there are relatively less settlements on the upper surface of the dam body. If the 3 nodal points on the surface of the dam body are examined, the nodal point 3557 has 0.3 m vertical displacement. In addition, the nodal points 3559 and 3561 which are at the upper elevations of the dam body, have approximately 0.5 m and 0.8 m settlements, respectively (Fig 6). When the vertical displacements are examined from the dam surface to the clay core, there are more settlements around the clay core.

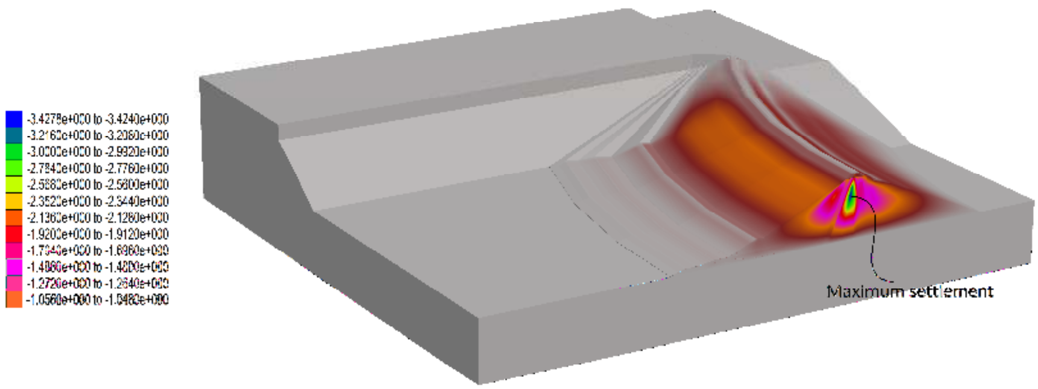

Figure 5. Vertical displacements (m) in Case 1.

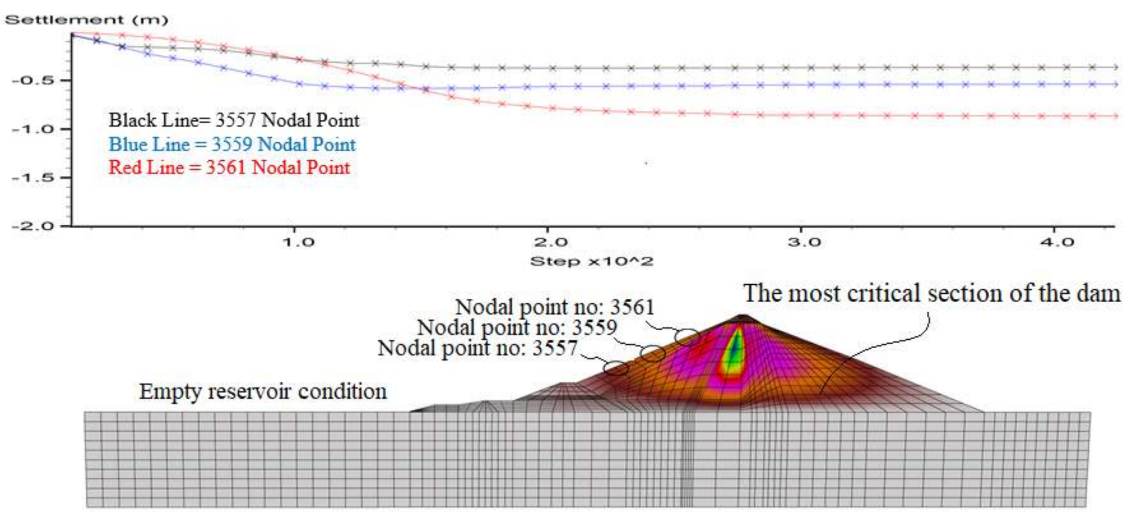

Figure 6. Vertical displacements (m) of 3 nodal points on dam body in Case 1.

3.2. Vertical displacements for full reservoir condition

Our numerical outcomes show that the hydrostatic pressure causes visible settlements in the body of the dam at full reservoir condition of the Atatürk Dam (Fig. 7). Vertical displacements are approximately 5.48 m at the clay core of the dam. In additional, approximately 3 m vertical displacements were observed around the cofferdam section. Maximum settlement is 0.6 m at the foundation which is under the dam body. Also, if Case 1 is compared with Case 2, an extra 2 m vertical displacement occurred on the surface of the dam. For nodal points 3557, 3559 and 3561, 4.9 m, 3.7 m and 3.2 m settlements were acquired respectively, in numerical analyses (Fig. 8). It appears that when the hydrostatic pressure increase from the crest of the dam to the foundation, there are more settlements in the bottom elevations of the dam body (Fig. 8).

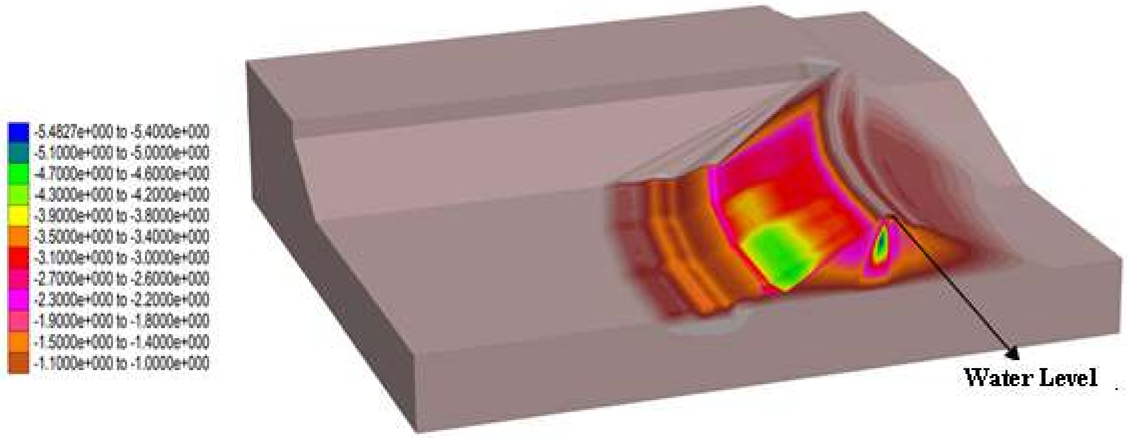

Figure 7. Vertical displacements (m) in Case 2.

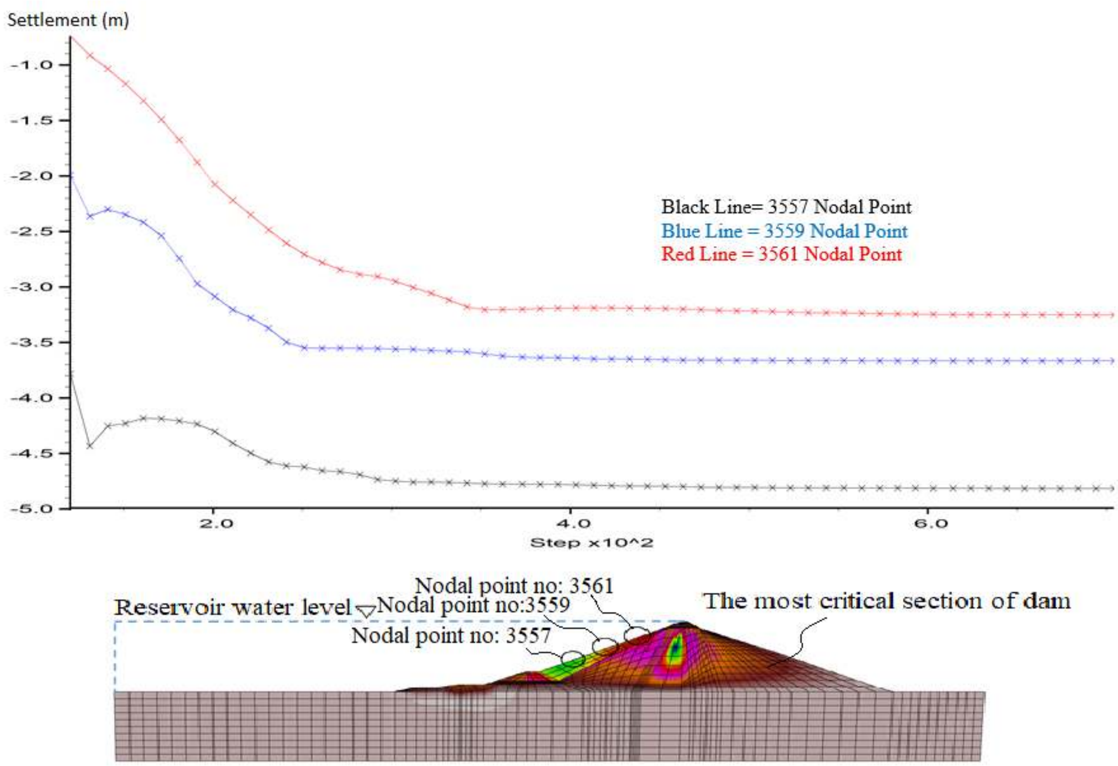

Figure 8. Vertical displacements (m) of 3 nodal points on dam body in Case 2.

Conclusion

We believe that it is extremely important to investigate the effect of reservoir water on the response of clay core rockfill dams in terms of safety. In order to understand how the behaviour of the dam changes with the reservoir water, we created 2 different finite element models of Atatürk Dam for two reservoir conditions, taking into account the dam-foundation-reservoir interaction. The selected water depth is 170 m. According to the numerical results, vertical displacements were examined and comprehensively evaluated for nonlinear analyses. Our results have led to the following conclusions:

- The present study clearly shows that maximum vertical displacement occurred in the clay core and this vertical displacement value is 3.42 m for empty condition of the reservoir water. When investigated vertical displacements from clay core to surface of the dam, vertical displacements clearly diminished.
- Maximum vertical displacement is 5.48 m in the clay core for full reservoir condition of the dam. In addition, if examined three nodal point of the surface of the dam body, maximum vertical displacement occurred at the lowest nodal point and minimum vertical displacement observed at the top nodal point.
- When the reservoir water is considered, vertical displacements increase due to the effect of hydrostatic pressure. If compared two reservoir conditions, minimum vertical displacements occurred for empty reservoir condition (Case 1) and maximum vertical displacement was observed for full reservoir condition (Case 2). This data provides a clear evidence for the effect of reservoir water on nonlinear behaviour of the dam.

References

[1] USACE: US Army Corps of Engineers (2004). ‘‘General Design and Construction Considerations for Earth and Rock-Fill Dams’’ Engineering and design (engineer manual) EM 1110-2-2300.
[2] Rezaei M.M., Salehi B. (2011). ‘‘The effect of changing the geometry and compaction degree on arching of earth dams’’ In: Geo-Frontiers Congress 2011 American Society of Civil Engineers (ASCE), 3207-3216.
[3] Kovacevic N., Potts DM., Vaughan PR. (1994). ‘‘Finite element analysis of a rockfill dam’’ In: Proceedings of the 8th International Conference on Computer Methods and Advances in Geomechanics, Morgantown, USA. 2459-2464.
[4] Duncan JM. (1996). ‘‘State of the art: limit equilibrium and finite element analysis of slopes’’ Journal of Geotechnical Engineering, 122(7), 577-595.
[5] Justo J.L (1991). ‘‘Collapse: its importance, fundamentals and modelling’’ Advances in Rockfill Structures, Dordrecht, Netherlands: Springer, 97-152.
[6] Naylor D.J. (1997). ‘‘Collapse settlement-some developments’’ Applications on computational mechanics in geotechnical engineering, Rotterdam: A.A. Balkema, 37-54.
[7] Cetin H., Laman M., Ertunç A. (2000). ‘‘Settlement and slaking problems in the world’s fourth largest rock-fill dam, the Ataturk Dam in Turkey’’ Engineering Geology, 56, 225–242.
[8] Zhan B., Wang J.G., Shi R. (2004). ‘‘Time-dependent deformation in high concrete-faced rockfill dam and separation between concrete face slab and cushion layer’’ Computers and Geotechnics, 31, 559–573.
[9] Yu Y., Xie L., Zhang B. (2005). ‘‘Stability of earth-rockfill dams: Influence of geometry on the three dimensional effect’’ Computers and Geotechnics, 32, 326–339.
[10] Zhang G., Zhang J.M. (2009). ‘‘Numerical modelling of soil-structure interface of a concrete-faced rockfill dam’’ Computers and Geotechnics, 36, 762–772.
[11] Fang C., Liu Z. (2011). ‘‘Stress-strain analysis of Aikou rockfill dam with asphalt-concrete core’’ Journal of Rock Mechanics and Geotechnical Engineering. 3(2), 186–192.

[12] Zhou W., Hua J., Chang X., Zhou C. (2011). ‘‘Settlement analysis of the Shuibuya concrete-face rockfill dam’’ Computers and Geotechnics, 38, 269–280.
[13] Xu B., Zou D., Liu H. (2012). ‘‘Three dimensional simulation of the construction process of the Zipingpu concrete face rockfill dam based on a generalized plasticity model’’ Computers and Geotechnics, 43, 143-154.
[14] Kartal M.E., Bayraktar A., Başağa H.B. (2012). ‘‘Nonlinear finite element reliability analysis of concrete-faced rockfill (CFR) dams under static effects’’ Applied Mathematical Modelling, 36, 5229–5248.
[15] Kim Y.S., Seo M.W., Lee C.W., Kang G.C. (2014). ‘‘Deformation characteristics during construction and after impoundment of the CFRD-type Daegok Dam, Korea’’ Engineering Geology, 178, 1–14.
[16] Pramthawee P., Jongpradist P., Sukkarak R. (2017). ‘‘Integration of creep into a modified hardening soil model for time-dependent analysis of a high rockfill dam’’ Computers and Geotechnics, 91, 104–116.
[17] Wen L., Chai J., Xu Z., Qin Y., Li Y. (2017). ‘‘Monitoring and numerical analysis of behaviour of Miaojiaba concrete-face rockfill dam built on river gravel foundation in China’’ Computers and Geotechnics, 85, 230–248.
[18] DSI, General Directorate of State Hydraulic Works, Regional Directorate, Ankara, 2018.