Case Study

An investigation on dam settlement during and end of construction using instrumentation data and numerical analysis

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Abstract

In the present study, using instrumentation data regarding vertical and horizontal displacement of the dam have been analyzed. Also, the largest and most critical section of the Marvak earth dam is modeled with the behavioral model of the Mohr–Coulomb by GeoStudio software. Numerical modeling of the dam has been done considering the actual embankment conditions and to analyze the changes of the immediate settlement during construction and the consolidation settlement just after construction and initial impounding. The outcomes of instrumentation and numerical analysis at the end of Marvak dam construction showed a settlement between 20 and 500 mm. The results show that the settlement will occur during the construction at the upper levels and the end of construction at the middle levels of the dam. By comparing observed and predicted data, multivariate regression and the explanation coefficient criterion (R^2) was found to be $R^2 = 0.9579$, which shows a very good correlation between observed and predicted data, and represents a good match for the settlement points and their location with the initial conditions of the design, and the behavior of the dam in terms of the settlement is found to be stable.

Keywords Settlement · Marvak earth dam · Instrumentation · Numerical analysis · End of construction

1 Introduction

Earth dams are important and huge structures whose foundation is not only on natural earth and rock materials, but also their raw materials are natural earth or rock materials, so continuous monitoring of earth dams is of special importance. Also, high construction costs, high damages due to dam failure and uncertainty in predicting the behavior of geotechnical structures due to the specific nature of soil materials, indicate the need for accurate monitoring of earth dams. Dam behavior is usually performed by the results of instrumentation and numerical analysis by various software including geostudio. In situations where the monitoring results are consistent with the results of the numerical analysis, it can be said that

the analysis shows the actual behavior of the dam and the results can be used to provide information to sections that do not have monitoring instruments. In fact, if a behavioral model with realistic parameters can be found that is well matched with the results of the instrument, this model can be used to predict the future behavior of the dam.

Clough et al. were the first researchers who utilized the finite element method in predicting the behavior of an earth dam in 1967. In the study, they used a linear elastic model to analyze stresses and deformations in the dam [1]. Then, Duncan and Chang, along with the development of computers and powerful software, used complex and nonlinear models of finite elements to demonstrate and analyze the stress–strain behavior of materials [2]. Nobari and Duncan used the finite element method to

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simulate humid environments. After that, the finite element method was seen as a powerful way to predict the behavior of earth dams [3]. A few years later, Zienkiewicz presented detailed reports on the static analysis of earth dams [4]. Abhilasha and Balan applied a commercial software that was studied by researchers and designers to model the seepage in earth dams and found that the results of modeling with Seep/w have acceptable accuracy [5]. Rashidi et al. assessed the pore water pressure and settlement of the Gavshan earth dam and the comparison of instrumentation data and numerical modeling using FLAC (2D) software concluded that dam performance in terms of pore water pressure, and finally stability of the dam is positive [6]. In another study, Rashidi et al. by examining and comparing the instrumentation's outcomes of the Siah Sang dam and numerical analysis using the Mohr–Coulomb model showed that the study dam is safer regarding the hydraulic failure just after the construction and the first impounding period compared to other rockfill dams in the world [7]. Karoui et al. investigated the numerical analysis of the behavior of the Seid El Barak dam and its comparison with instrumentation data [8].

Luo et al. examined the Chengbehi dam monitoring for 18 years using piezometric pressure and settlement results and found that the maximum settlement in the middle of the dam was 178 mm, which gradually decreased from the middle to the sides. The maximum settlement in the wings was 65.8 mm. Also, due to water pressure in the tank, more settlements were observed upstream of the cutoff wall [9]. Sukkarak and Jongpradist in their study of rockfill dam's settlement found that the geometry of the dam is very important, especially in narrow valleys in terms of the settlement. During impounding and operation, the dam body withstands all internal and external loads [10]. This often causes horizontal and vertical displacements, called vertical settlement locations (Ik-Soo) [11]. Although major displacements occur during the dam construction, the investigation of the earth dam's settlement sometimes leads to effective results. In general, the maximum settlement of the dam is in its midpoints and gradually decreases until it reaches zero in the paws. Because of the settlement, the structure of the dam gradually stretched and the distance between the tiller's slopes along the base slightly increases

(Gikas and Sakellario) [12]. Silvani et al. investigated the effect of buoyancy force and the decrement in the friction using the Distinct Element Method (DEM) coefficient in a rockfill column [13].

In this study, first, the results of horizontal and vertical displacement monitoring of the Inclinator and settlement instrument installed in the core of the Marvak are investigated. Then, the settlement of the earth dam studied was investigated through finite difference numerical modeling, Geostudio. Finally, by comparing and verifying the recorded data of settlement piezometers and making sure that they do not contradict existing theories in geotechnics, a comparison is made between the results of real instruments and numerical methods.

2 Materials and methods

2.1 Case study

Marvak Dam was constructed on the river of Tireh 38 km far from Dorud City, situated in the province of Lorestan, Iran. The dam is an earth dam with having clay core. The construction aims of the dam are to provide storage (about 120 mcm/y) to Tireh, to supply the water required for agriculture in the Silakhor plain (5400 hectares area) located downstream of about 50 mcm, to arrange the water needs of downstream lands and to control flood. The dam has a height of 68 m from the bedrock, a length of 451 m, and a width of 10 m, normally reservoir has a 60-mcm volume, an elevation (crest) of 1621 masl, the area of the reservoir is 45.5 km², and the length of the lake is 4.5 km when the reservoir level reaches its maximum. The dam has a volume (embankment) of 3,670,000 m³. Construction of the Marvak Dam began in 2003 and was completed in 2014. The situation of the Marvak Dam is illustrated in Fig. 1. In Iran and Lorestan province. Table 1 displays the specification of the dam materials.

The Marvak Dam instrumentation has been designed in seven transverse sections and different levels, with 27 Inclinator (in-place) and 8 Inclinator and settlement meter on different levels. The first instrument of the dam was installed in the year 2008. The instrument

Fig. 1 The critical section of the Marvak Earth Dam with the position of the installed instruments (Sec. 10)

Table 1 Marvak dam profile, (instrument report, Abfan Consulting Engineers [14])

Dam type	Earth dam having clay core
Crest length (m)	451
Core volume (m ³)	453,000
Reservoir volume (mcm)	120
Normal water level (masl)	1617
Crest width (m)	15
Upstream cofferdam height (m)	30
Downstream cofferdam height (m)	36

for measuring and controlling internal deformations of the body and core of the Marvak Dam is the use of the Inclinator and settlement instrument at different levels. With the help of this tool, you can check the horizontal and vertical displacement of the core and the downstream shell at different points and, if necessary, control the level of the reservoir's water. Besides, the amount of settlement, shell, and foundation at the time of the dam is obtained. In this study, section number 10 has been investigated considering the installation of the most inclinometers and settlement instrument (Table 2).

2.2 Construction stage deformations

When building the body of an earth or rockfill dam, the weight of the material and its gradual increase (with increasing the height of the dam) causes the settlement of the body. Figure 2 shows the vertical deformation (settlement) of a horizontal layer at a depth of h .

It is assumed that the settlement plate is located at point P at height h . At each section such as h , the value of vertical deformation δ_v is obtained at a point such as P and for embankment at height H according to the following equations:

$$\varepsilon = m_v \cdot \Delta\sigma \quad (1)$$

$$= m_v \cdot h \cdot (H - h)$$

$$\delta_v = m_v \cdot h \cdot (H - h)\gamma \quad (2)$$

In these relations ε : relative deformation for each stress increase by $\Delta\sigma$, $\Delta\sigma$: increase in vertical stress, m_v : material ductility coefficient, γ : weight per unit volume of embankment material, H : total dam height, h : body point height of the body Dam concerning its base, δ_v : The total amount of vertical deformation (settlement) at point P. According to Eq. 2, it is observed that the changes of δ_v concerning height are parabolic. That is, the seismometer installed

Table 2 Instrumentation of Marvak Dam (instrument report, Abfan Consulting Engineers [14])

Kind of instrument	Number of instruments										Total				
	Section 1		Section 5		Section 8		Section 10		Section 13			Section 15		Section 16	
	Level (masl)	Num	Level (masl)	Num	Level (masl)	Num	Level (masl)	Num	Level (masl)	Num		Level (masl)	Num	Level (masl)	Num
Surface Settlement (SS)	1621.5	2	1590	2	1608	1	1590	1	1575	2	1575	2	1575	1	27
			1608	1	1621.5	2	1608	1	1590	1	1590	1			
			1621.5	2			1621.5	2	1608	1	1608	1			
Inclinometer Settlement (IS)			1565	1	1530	2	1525	1	1550	1	1621.5	2			8
							1530	1	1565	1					
							1535	1							

Fig. 2 The process of deformation during the construction of an earth dam

at point P indicates the maximum value that P is in the middle of the layer and if position P is at the top or bottom of the layer; The deformation value will be zero. Of course, assuming that the dam is located on a very strong foundation.

2.3 Introduction of Marvak Dam behavioral model

The soil in nature is rarely classical (homogeneous isotropic and elastic). Therefore, in important geotechnical issues, it is necessary to select an advanced behavioral model for modeling nonlinear and time-dependent behavior. Although a simple behavioral model does not require a high number of parameters, its analysis outcomes may differ greatly from the measured values. On the other hand, the complex behavioral model needs more parameters, which are difficult to determine both economically and laboratory-wise. Hence, deciding the right models is an important issue for engineers. In this study, the results of vertical and horizontal displacement of precision instruments installed during the construction of Marvak Dam have been studied and compared with the results of numerical analysis obtained using the Geostudio software which is an integrated software suite for simulating slope stability, heat, and mass transfer and ground deformation in soil and rock. According to the appropriate results of soil and stone behavior, the Mohr–Coulomb elastoplastic model for foundation and other material of Marvak Dam was used. Since this model presents most of the soil-related parameters (e.g., dough and plastic soil), it is suitable to demonstrate most soil

behavioral conditions. The elements used to mesh the dam, other parts of the FEM models were quad and triangle shapes. In general, the most important issue in the analysis of any structure by numerical analysis is the introduction of model parameters. In Marvak Dam, design parameters and assumptions, and test results of construction time have been used for modeling and initial analysis. Appropriate boundary conditions in numerical modeling, geometric shape of the model, demarcation, and meshing have been selected based on the guidelines of the National Committee of Large Dams for the analysis of Marvak earth dam. In the main model, 2670 elements and 3105 nodes were utilized. To apply the appropriate boundary conditions in numerical modeling, the geometrical form of the model, boundary, and grid were selected according to the guidelines of the National Committee of Large Dams for earth dam analysis. In this section, most of the parameters are considered from design hypotheses and test results at construction time for initial modeling and analysis. Table 3 reports the materials' characteristics of Marvak Dam utilized in numerical analysis. The core of the dam (not completely drained) at the end of construction is considered saturation due to the moisture of the material during compaction and also the compaction of the material due to the weight of the upper layers. Also, because it is not possible to have proper and complete drainage for the materials at the time of construction, the core materials are not consolidated at the end of the dam construction. Process and solution algorithm is described in Fig. 3.

Table 3 Initial values of mechanical parameters of the building materials and dam body, instrument report of Marvak Dam (2012)

Material	Model: Mohr–Coulomb	Material type	γ_{dry} (kN/m ³)	γ_{wet} (kN/m ³)	γ_{sat} (kN/m ³)	E (MPa)	ν	c (kPa)	ϕ (°)
Core	Elasto-plastic	Undrained	17	20	21	50	0.48	43	11
		Drained					0.35	30	25
Shell	Elasto-plastic	Drained	22.5	23.8	24.5	200	0.20	–	38
Filter	Elasto-plastic	Drained	19	21	22	100	0.25	–	30
Drain	Elasto-plastic	Drained	20.5	22	23	150	0.20	–	35
Foundation	Elasto-plastic	Drained	28	–	25.5	4000	0.10	–	42

Fig.3 Back analysis method and solution algorithm

3 Results and discussion

3.1 Analysis of horizontal and vertical displacements at the stepwise construction of embankment

Displacement of earth dams includes vertical and horizontal displacements. Vertical displacements indicate that the settlement is related to the weight of the material, and the consolidation of the dam material. Horizontal displacement mainly refers to the upstream movement of the dam due to the impounding of the dam reservoir, which is associated with the rapid reduction of effective stresses upstream of the dam compared with other parts of the dam and the downward movement of the dam due to hydrostatic force caused by the dam reservoir. It is difficult to estimate and calculate the exact amount of settlement during construction. Because the quantities are continuously changing with the continuation of the excavation and loading onto the previous layers. Therefore, at the same time, the loading and characteristics of excavation materials are changing, which makes it difficult to accurately estimate the size of the settlement. Of course, the major settlements of the construction time are an immediate or elastic settlement. The instantaneous settlement is affected by the elastic behavior of materials due

to the successive loading of new layers on the underlying layers and in a short time. The dam construction is modeled by dividing the height of the dam for the critical section into 13 layers, and is average, according to the study reports of each layer in 65 days, and the height of each layer is approximately 5.5 m. In this research, the results of the dam instrument settlement are analyzed by time at the end of construction and the first impounding with the outcomes of numerical modeling. At this stage, the level of settlement is evaluated after the implementation of each soil layer. In the modeling of the foundation, before the construction of the dams, the weight of the embankment was considered zero. The vertical settlement rate is close to zero at this stage and there is not much change in the settlement. Also, the problem is in the core and shell state in the mode of linear analysis. At this stage, settlement after each layer of soil was investigated. The first embankment layer is modeled after foundation analysis. The results of the horizontal and vertical displacements of the Marvak Dam with 65 days of embankment implementation for each layer are shown in Figs. 4 and 5.

According to Figs. 4 and 5, as the soil layers increased and the layer-by-layer construction of the Marvak Dam increased, maximum settlement from the first layer about 60 mm, eventually increased to about 280 mm in the last layer (layer 13). Hence, in each step of the dam

Fig. 4 Layer-by-layer analysis of horizontal displacement of the Marvak Dam core

construction, enough time should be allowed for the consolidation and settlement and, also for lowering pore water pressure due to the dam core's low permeability, and the prevention of high-speed dam construction at a low time. Also, most of the horizontal displacements of the Marvak dam core occurred at about 40 mm above the upper elevations of the core and prone to downstream shells (there are two layers of filter and drain), which is negligible. The results of the analysis show that during the construction due to instant consolidation, most of the settlements occurred at the top of each layer. Finally, in the

last layer, the most settlement occurred near the dam crest (Figs. 6, 7).

3.2 Analysis of horizontal and vertical displacements after dam construction

The outcomes of the numerical modeling show the maximum settlement at the end of construction at 510 mm. As the phenomenon of consolidation is usually time-dependent and the dam core has low permeability and the settlement will increase over time, therefore, the settlement rate

Fig. 5 Layer-by-layer analysis of settlement of the Marvak Dam core

should be considered because with the increasing vertical settlement, the probability of crack and hydraulic fracture at the dam bottom is increased. Given that the software results are bound up with the end of the construction stage. Also, the changes in horizontal displacement after the end of construction and the first impounding due to the water pressure of the dam reservoir are relatively noticeable for the upstream and downstream shells, but the changes in horizontal displacement for the core will not be significant and have reached a maximum of 60 mm (Fig. 8).

Therefore, the results of the software were evaluated with the actual instrumentation results at the end of the construction phase, in the year 2013, and the dam is in its first impounding period. Low permeability of clay core materials and consequently prolonged and gradual drainage lead to post-construction consolidation and immediate settlement at the time of dam construction, which is why the results of the Marvak Dam instrument settlement during construction were less than the end of construction and the first period of impounding (Fig. 9).

Fig. 6 The settlement at the core during construction

Fig. 7 Horizontal displacements at the core during construction

Fig. 8 Horizontal and vertical displacements at the core during construction

The maximum settlement occurred at the 1587 m level and in the middle of the dam height above the foundation level and was reported to be 498 mm. Generally, the

piezometers are located in the dam between 200 and 500 mm. In Fig. 10, the results of the inclinometer instrument of the dam are shown in the construction phase.

Fig. 9 Time variation of the settlement at the core

Fig. 10 Core settlement during construction (instrumental results)

Fig. 11 Comparison of observed values and predicted values of Marvak Dam

The curve of the instrumentation change settlement is the same as the vertical settlement change curve (numerical analysis) from the beginning to the end of the construction of the Marvak Dam, and the software results and the instrumentation of the dam match are very good (Fig. 11). Also, according to the results, the dam is settlement symmetrically. The level of horizontal displacement in the dam construction phase is very small, about zero. Therefore, the construction phase of the dam will not have much effect on horizontal displacement. However, after the dam is impounded, the

Fig. 12 Distribution diagram for observed and predicted values (GeoStudio)

horizontal displacement increases due to the reservoir water pressure.

Multivariate regression has been applied with an explanation determination coefficient (R^2) to assess the performance of instrumental results and the GeoStudio model.

$$R^2 = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - O_{ave})^2} \quad (3)$$

In relation (3), n indicates the quantity of data, O_i and P_i are the measured or observed and predicted values, and O_{ave} is the average of the measured values. The R^2 is an indicator to explain how the measured values are close to the fitted line. The closer the R^2 to 1 is, the more model performance is shown. If $R^2 = 1$, it indicates a perfect or ideal fit. By using the relation (3), R^2 was found as 0.9579 for the outcomes of the GeoStudio software, which indicates the correspondence between the results of the meeting for the values of the actual instrument and the predicted values (Fig. 12). A comparison of instrument data and numerical analysis is at the core axis of Marvak Dam.

4 Conclusion

In the layer-by-layer implementation of the dam, the settlement occurred above the core and near the dam crest. Also, the settlement at the end of construction and the first period of impounding in the middle of the core occurred. The step construction of the dam is simulated for modeling in real construction conditions by dividing the height of the dam for the critical cross-section into 13 layers. According to the results of the instrument, the maximum settlement occurred at the end of the construction phase

at level 1587 m and in the middle of the dam height. For these reasons, we consider that the settlement characteristics observed for the dam embankment can be related to a combination of moisture content variation within the central core zone of the dam combined with a lack of substantial stiffness from the enclosing rock fill zones. The results of the (real) instrumentation change curve correspond to the vertical (numerical analysis) curve change from the beginning of the construction to the end of the construction of the Marvak Dam. By comparing the observed and predicted data from the multivariate regression, the coefficient of determination coefficient $R^2 = 0.9553$ was obtained which shows very good agreement between the observed and predicted data. Where the values of the settlement and their location correspond to the initial design conditions, the dam is stable in terms of settlement just after the dam construction. In the future, researchers can provide a suitable model for predicting settlement by comparing the results of earth dam settlement instruments with the results of different models of the neural network.

Compliance with ethical standards

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