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Change of Pore Water Pressure Inside the Foundation of Alavian Earthfill Dam, Iran: A Comparison Between Observed and Predicted Values

Mohammad H. Aminfar, Bahman Farahmand Azar, Hosein Ebadi and Hamid Ahmadi
Faculty of Civil Engineering, University of Tabriz, 29 Bahman Blvd., Tabriz, Iran

Abstract: Investigation of dam behavior during the construction and service phases is a very useful tool to control, to correct and to optimize the design process and to provide required contrivances during these phases. The aim is to prevent the probable damages and destructions and to maximize the commercial efficiency of the project. Because of mentioned reasons, installation of suitable instrumentations for analysis of effective parameters in performance and stability of dam during different periods is inevitable. In the present study, behavior of pore water pressure inside the foundation of Alavian dam (Iran) is studied. Plaxis is used to model the dam and the predicted results are compared with the measured ones. Then, the effect of foundation and cut-off wall permeability on the distribution of pore water pressure inside the foundation is investigated.

Key words: Instrumentation, earth-fill dam, pore water pressure, alavian dam, plaxis

INTRODUCTION

In the present study, change of pore water pressure inside the foundation of Alavian dam (Iran) during the initial period of service is investigated and the parameters controlling the behavior of dam are studied. Alavian dam was built at Soufi-Chay River, Southwestern Iran. It is located on southern hillside of Sahand Mountain, southeast of Urmia Lake and at the distance of 120 km from Tabriz. Geometrical characteristics of Alavian dam are presented in Table 1 and the values of reservoir volume for different levels of water are given in Table 2. To better understand the behavior of dam, its largest section is modeled and analyzed by Plaxis and the values predicted by Plaxis are compared with the measured values. Sadrekarimi (2000) described the fundamental concepts of pore water pressure measurement in earth-fill dams and error resources. Sadrekarimi *et al.* (2003) compared some predicted and observed behaviors of Alavian Dam. In the present research, after comparing the predicted and observed behavior of pore water pressure inside the dam foundation, effect of foundation and cut-off wall permeability on the distribution of pore water pressure inside the foundation is investigated.

The characteristics of Alavian dam: Alavian dam is a non-homogenous (zoned) earth fill dam with a central impervious core flanked by pervious shells. To protect the upstream slope, a 1.5 m thick layer of stone riprap is used. An injection gallery was build by concrete blocks under the core and on the bed rock for injection, inspection, repair, piezometer installation, etc. Some geomechanical specifications of materials used in dam body are given in Table 3.

Bedrock is formed from tuff which includes fully weathered tuff and the tuff with medium weathering in surface layers. At the river bed, it is covered by sedimentary materials. Profile of the materials forming the foundation and bed is shown in Fig. 1. Sedimentary formation includes claystone with some conglomerate localities. Some geological specifications of tuff layers and alluvial materials are shown in Table 4 and 5, respectively.

Table 1: Geometrical characteristics of Alavian dam

Height from river bed	70 m
Height from dam foundation	76.8 m
Length of dam crest	935.0 m
Width of dam crest	10 m
Total volume of embankment (dam body)	4769000 m^3
Surface area of reservoir	262 ha

Table 2: Values of reservoir volume for different levels of water

Water level	Total volume (m^3)
Normal (1568)	60e6
Maximum (1572)	72.65e6
Minimum (1525)	3e6

Table 3: Geomechanical specifications of materials used in dam body

Zone	Unified classification	Maximum dry density (g cm^{-3})
Shell	Rubbles and GW	2.05-2.10
Filter and transition	SW	2.05-2.10
Core	CL-CH	1.56-1.79

Corresponding Author: Mohammad H. Aminfar, Faculty of Civil Engineering, University of Tabriz, 29 Bahman Blvd., Tabriz, Iran Tel: 00989143112813 Fax: 00984113344287

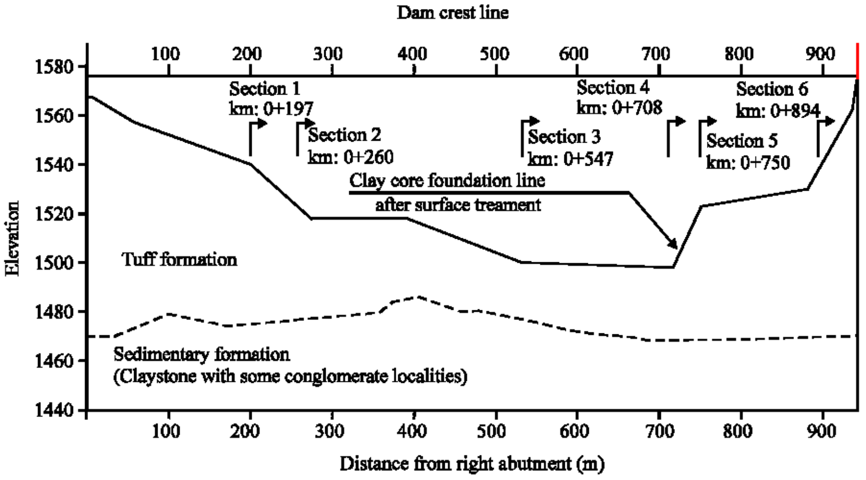

Fig. 1: Profile of the materials forming the foundation and bed of Alavian dam (Sadrekarimi *et al*., 2003)

Table 4: Geological specifications of tuff layers

Stone type	Degree of weathering	RQD (%)	Weight per volume (kN m^{-3})	Porosity (%)	Internal friction angle (degree)	Cohesion (kN m^{-2})	Averaged permeability (m sec^{-1})
Claystone	Very low	95-100	21-23	5-15	21-25	750	1e(-10)
Tuff- class A	Low	90-100	18-21	16-34	20-22	600	1e(-07)
Tuff- class B	Medium	75-90	18-21	21-35	20-22	500	0.0005
Tuff- class C	High	50-75	18-21	26-46	19-22	300	0.05

Table 5: Geological specifications of alluvial materials

Soil type	Internal friction angle (degree)	Cohesion (kN m^{-2})	Averaged permeability (m sec^{-1})
River alluvial	35	0	0.07-0.2
Saturated clay	10	20	1e(-07)
Unsaturated clay	25	30	-

Cut-off wall: A cut-off wall is constructed by a set of primary and auxiliary boreholes. Depth of primary boreholes is 50 m and their distance from each other is 1.25 m and they are arranged in a single row. Auxiliary boreholes are 30 m in depth and are arranged in two rows at the upstream and downstream of cut-off wall. Consolidating injection is used to increase the quality of bed rock and to control the water leakage. A net of shallow boreholes which are 7.5 m in depth are used for this purpose.

Instrumentation used in Alavian dam: A complete set of instrumentation is installed in Alavian dam to observe its behavior during the construction and service phases. Main functions of the installed instrumentation are:

- Measurement of horizontal and vertical movements of body and foundation of dam
- Detection and measurement of leakage through the body and foundation of dam
- Measurement of pore water pressure in the body and foundation of dam
- Measurement of dynamic water surface level in the body and foundation of dam
- Measurement of earthquake intensity (Sadrekarimi *et al*., 2003)

The plan of geodesic points and locations of six instrument installation sections are shown in Fig. 2. Third instrument installation section which is the largest section of dam is shown in Fig. 3. This section is studied in the present research.

To study the changes of pore water pressure, a complete set of vibrating wire piezometers, mechanical piezometers, hydrogeological boreholes and standpipe piezometers are used in the body and foundation of dam. Electrical vibrating wire piezometers are installed in the dam foundation, on contact surface between bed rock and core and inside the core. The objective of installation of piezometers in the foundation is investigation of cut-off wall performance. The transducers of these piezometers are installed in the borehole without protective walls at the depth of 8, 15 and 25 m. The diameter of these boreholes is 59 mm. Main functions of piezometers installed on contact surface between bed rock and core are to determine the pore water pressure distribution inside the core and to indicate the leakage routs through the contact surface.

Eighty total pressure vibrating wire cells- 3 cells in each section which are installed on central line, upstream

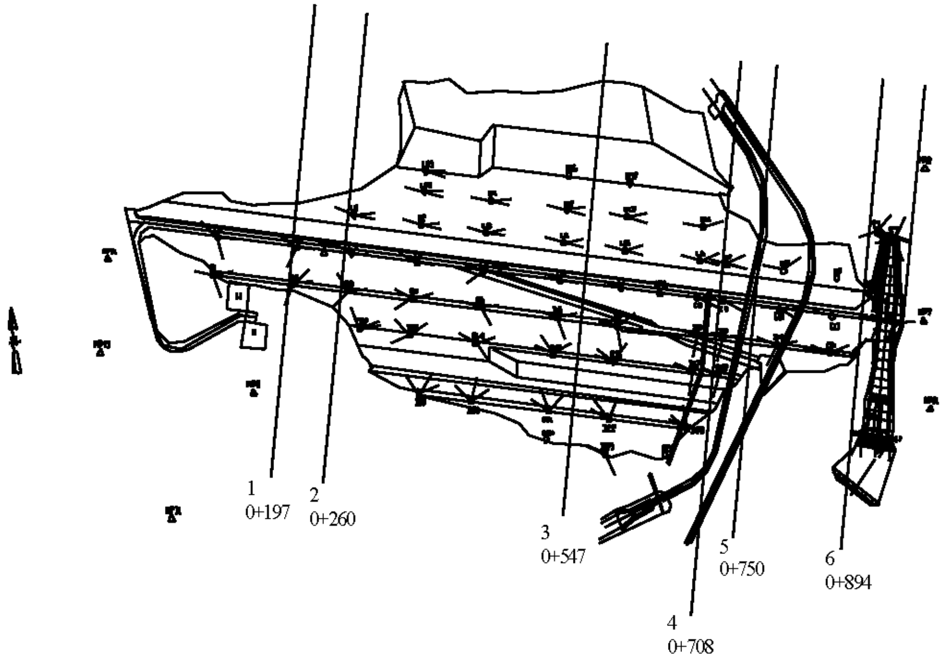

Fig. 2: The plan of geodesic points and locations of six instrument sections

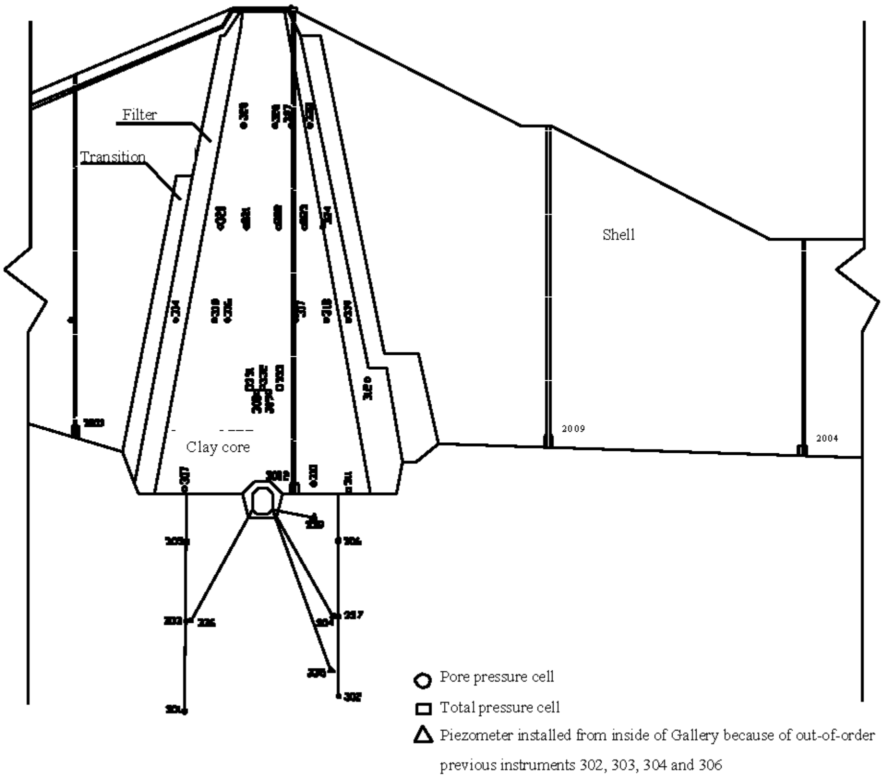

Fig. 3: Third instrument installation section (only the centric segment of section is presented)

of central line and downstream of central line of the core- are used to measure the total pressure inside the core.

GENERAL CONSIDERATIONS OF NUMERICAL STUDY

Plaxis, a powerful FE software package, is used to analyze the mechanical behavior (such as stress, deformation, etc.) of soils and rocks. This package can be used for water flow calculations in soil and rock environments. Plaxis has special tools for graphical modeling of earth-fill dams and the results of analysis can be exported to other programs for assessment. Also this software can model pore water pressure in steady-state flow and various soil behavior models are available in this package. Moreover, change of permeability in the layers which are located at the different depth can be considered in the models generated by Plaxis. Plaxis can be used for 2D and 3D analysis. 6 and 15 nodes tetrahedral elements are available for mesh generation.

Behavior models to investigate the pore water pressure: Three different behaviors can be assigned in Plaxis to model the existence of water in the soil:

- **Drained behavior:** If this behavior model is used, no excessive pore water pressure is generated. So, this model is suitable for dry soils and fully drained soils with high permeability such as sands. In addition, this model can be used in low speed loading conditions
- **Undrained behavior:** In this case, pore water pressure can be fully developed. This behavior model can be used for the soils with low permeability such as clays. Moreover, this model can be used in high speed loading conditions
- **Non-porous behavior:** If this model is used for a cluster of soil, both initial and excessive pore water pressures are excluded from the calculations

Hydraulic conditions: Generally, Plaxis is used to calculate the effective stresses. It must be noted that active pore water pressure can be calculated as follows:

$$P_{active} = P_{steady} + P_{excess} \quad (1)$$

where, P_{active}, P_{steady} and P_{excess} are active, steady-state and excessive pore water pressure, respectively.

Excessive pore water pressure is generated due to loading the clusters with undrained behavior and steady-state pore water pressure is related to a constant hydraulic condition which can be resulted from a long-time constant external pore water pressure (Sadrekarimi, 2000).

Theoretical concepts of pore water pressure and flow calculations in plaxis: Since the soil pores are very small, the flow through most soils is laminar. This laminar flow is governed by Darcy's Law which is also used in Plaxis for flow calculations. To describe the flow in saturated and unsaturated soils, a reducing function K^r is used in Darcy's Law. Above the water surface level, value of K^r is 1 and under the water surface level, its value is lower than 1 and is relatively small which is shown by α.

Near the water surface level, there is a transition region. In this region, K^r is linearly changes between 1 and β. Transition range which is defined by a parameter called β depends on the used element and mesh generation method.

Modeling and analysis: Embankment progress trend line and water level in the reservoir during scheduled construction of dam is shown in Fig. 4. These data must be used to model the scheduled construction of dam body by Plaxis. The objective of this model is to compare the predicted values of pore water pressures with the measured ones and to investigate their changes by time in specific dates.

Mohr-coulomb behavior model was assigned in Plaxis to calculate pore water pressure and the predicted results were compared with the measured ones. Six nodes tetrahedral elements with plain-strain condition were used for mesh generation. Also, drained behavior was assigned for both body and foundation of dam.

Two main considerations of cut-off wall modeling are listed below:

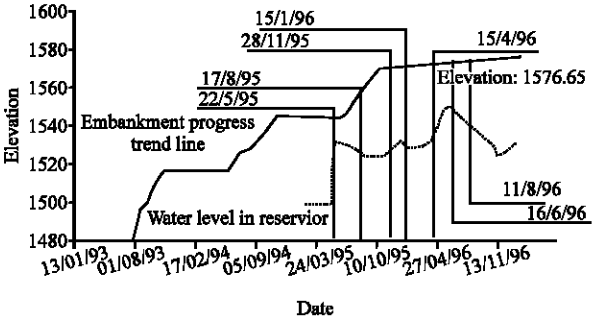

Fig. 4: Embankment progress trend line and water level in the reservoir during scheduled construction of dam

- Width and depth of cut-off wall effect zone are 2 and 50 m, respectively
- Change of average permeability in depth is considered up to depth of 80 m under the core bed. Deeper layer which is claystone has very small permeability (10^{-10} m sec^{-1})

RESULTS AND DISCUSSION

Pore water pressure inside the foundation of dam: It must be noted that initiation and development of pore water pressure inside a rock bulk are the results of existence of cracks and discontinuities. In addition, a soil or rock bulk has different permeability in vertical and horizontal directions. Also, spatial distribution of the fissures and types of the materials are not the same. So, different regimes of pore water pressure would be expected (Memarian, 1998).

The change of predicted and observed pore water pressure by time at the depth of 7.5, 19.5 and 33 m (piezometer installation levels of 3rd section) are shown in Fig. 5-7. Water height and water level in the reservoir during the considered time ranges are given in Table 6.

Effect of foundation and cut-off wall permeability on the distribution of pore water pressure inside the foundation: To investigate the effect of cut-off wall and foundation permeability on the distribution of pore water pressure, four models with different foundation and cut-off wall permeability were analyzed and the predicted values were compared with observed ones. Specifications of these four models are given in Table 7. The results are presented in Fig. 8-13.

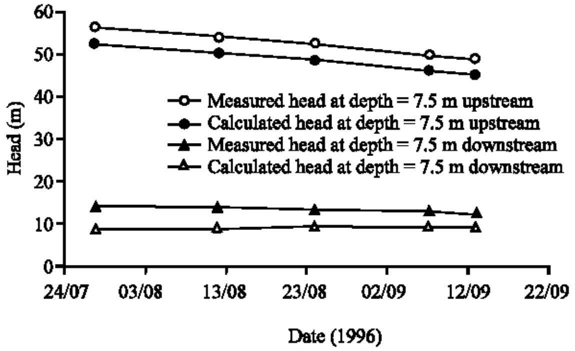

Fig. 5: Change of predicted and observed pore water pressure at the depth of 7.5 m, cut off downstream and upstream, date: 1996.07.28 to 1996.09.13

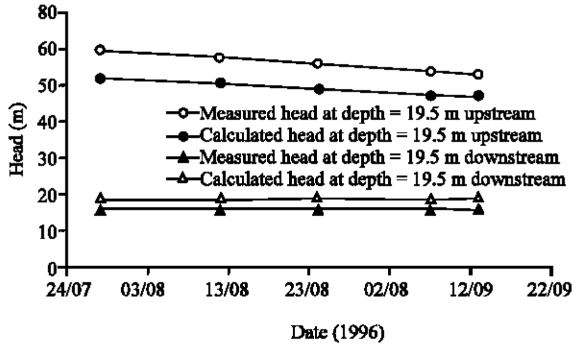

Fig. 6: Change of predicted and observed pore water pressure at the depth of 19.5 m, cut off downstream and upstream, date: 1996.07.28 to 1996.09.13

Table 6: Water height and water level in the reservoir during the considered time ranges

Date	No. of days	Dam level	Dam height (m)	Reservoir level	Water depth on reservoir (m)	Water depth decrement (m)
28.07.1996	0	1576.65	76.80	1544.52	48.52	0.00
12.8.1996	15	1576.65	76.80	1542.32	46.32	2.20
24.8.1996	14	1576.65	76.80	1540.52	44.52	1.80
7.09.1996	15	1576.65	76.80	1538.12	42.12	2.40
13.09.1996	7	1576.65	76.80	1536.96	40.96	1.16
-	-	1576.65	76.80	NWL^A	72.00	-
-	-	1576.65	76.80	MWL^A	76.00	-

^{A}NWL: Normal water level, MWL: Maximum water level

Table 7: Specifications of four models used to investigate the effect of cut-off wall and foundation permeability on the distribution of pore water pressure

Model No.	Permeability (m sec^{-1})	Zone Tuff- No. 1	Tuff- No. 2	Tuff- No. 3	Tuff- No. 4	Claystone	Cut-off
1	K_x	1e(-2)	1e(-3)	1e(-4)	1e(-5)	1e(-10)	1e(-8)
	K_y	1e(-3)	1e(-4)	1e(-5)	1e(-7)	1e(-10)	1e(-8)
2	K_x	1e(-3)	1e(-4)	1e(-5)	1e(-6)	1e(-10)	1e(-7)
	K_y	1e(-4)	1e(-5)	1e(-6)	1e(-8)	1e(-10)	1e(-7)
3	K_x	1e(-4)	1e(-5)	1e(-6)	1e(-7)	1e(-10)	1e(-7)
	K_y	1e(-5)	1e(-6)	1e(-7)	1e(-9)	1e(-10)	1e(-7)
4	K_x	1e(-4)	1e(-5)	1e(-6)	1e(-7)	1e(-10)	1e(-9)
	K_y	1e(-5)	1e(-6)	1e(-7)	1e(-9)	1e(-10)	1e(-9)

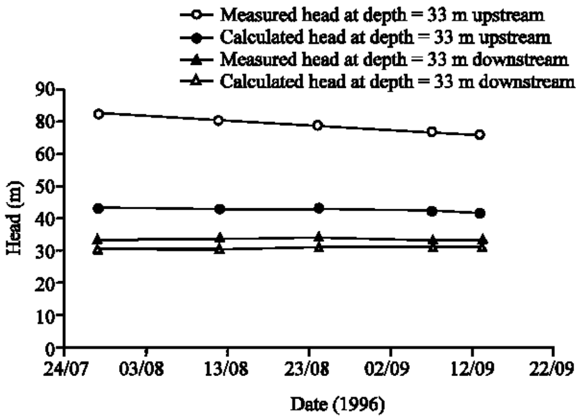

Fig. 7: Change of predicted and observed pore water pressure at the depth of 33 m, cut off downstream and upstream, date: 1996.07.28 to 1996.09.13

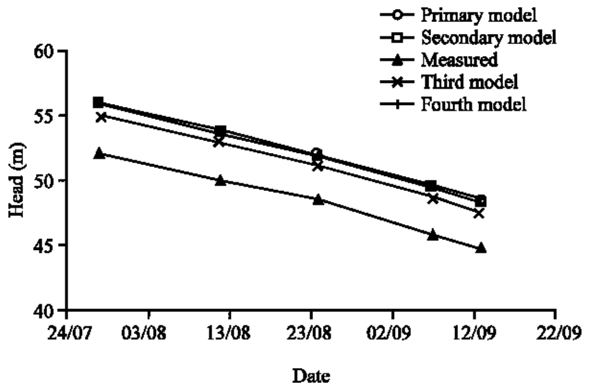

Fig. 8: Change of pore water pressure at the depth of 7.5 m, cut-off upstream

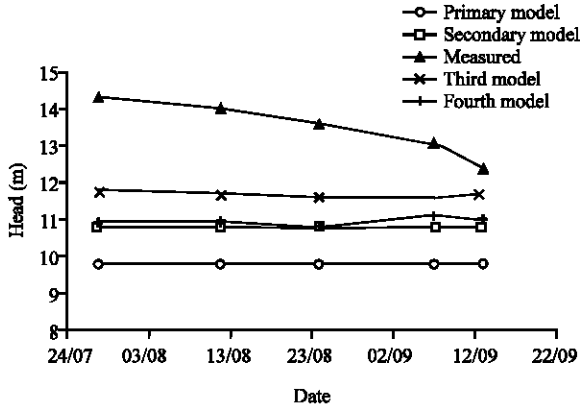

Fig. 9: Change of pore water pressure at the depth of 7.5 m, cut-off downstream

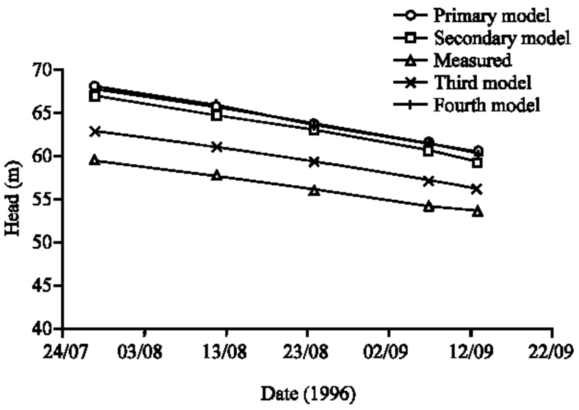

Fig. 10: Change of pore water pressure at the depth of 19.5 m, cut-off upstream

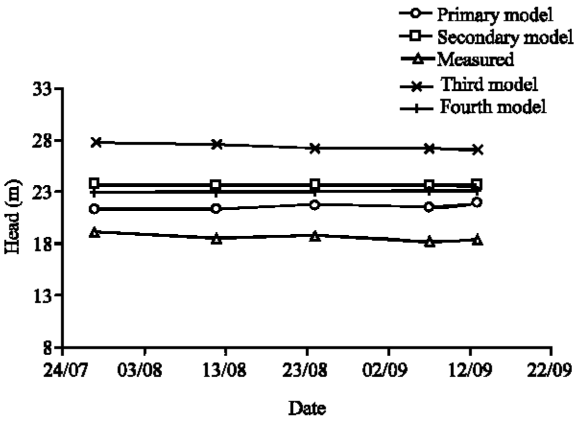

Fig. 11: Change of pore water pressure at the depth of 19.5 m, cut-off downstream

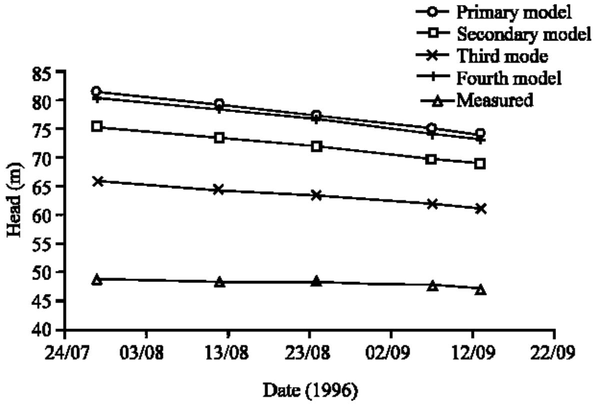

Fig. 12: Change of pore water pressure at the depth of 33 m, cut-off upstream

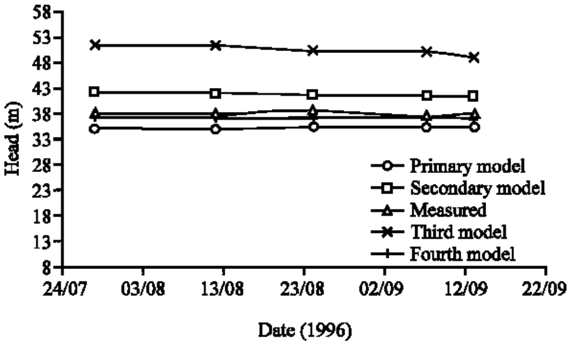

Fig. 13: Change of pore water pressure at the depth of 33 m, cut-off downstream

CONCLUSIONS

Pore water pressure behavior inside the foundation:

- The results showed that 8 m decrement in water level in the reservoir during 60 days led to descending trend in diagrams of predicted and observed pore water pressure. Gradient of this decrement at the upstream of cut-off wall is higher than its gradient at the downstream of cut-off wall. In addition, predicted and observed pore water pressure diagrams are approximately of equal slope at the cut-off wall upstream
- The difference between the pore water pressure diagrams at the upstream and down stream of cut-off wall indicates the effect of cut-off wall on the pressure distribution and shows that whatever the depth is increased, the effect of cut-off wall is decreased

Effect of cut-off wall and foundation permeability on the pore water pressure inside the foundation:

- It can be seen from Fig. 8-13 that in all cases, the predicted pressure is higher than the observed pressure excluding the values at the depth of 7.5 m, cut-off wall downstream
- It can be seen from comparing the 1st and 2nd models that when the permeability of foundation layers is decreased by 90% and the permeability of cut-off wall increased by 900% (2nd model), pressure heads are increased at the upstream while they are decreased at the downstream. Minimum change occurred at the depth of 7.5 and maximum change was equal to 7 m and occurred at the depth of 33 m
- It can be seen from comparing the 2nd and 3rd models that when the permeability of cut-off wall remains unchanged while the permeability of foundation is decreased by 90%, pressure heads are increased at the upstream while they are decreased at the downstream. Maximum change was equal to 10 m and occurred at the depth of 33 m
- It can be seen from comparing the 3rd and 4th models that when the permeability of foundation layers remains unchanged while the permeability of cut-off wall is decreased by 99%, pressure heads are increased at the downstream while they are decreased at the upstream. Maximum change was equal to 12 m and occurred at the depth of 33 m
- It can be seen from comparing the 1st and 4th models that when the permeability of foundation layers and cut-off wall are decreased by 99 and 90%, respectively, pressure heads are slightly decreased at both downstream and upstream of cut-off wall. Rate of decrement at the upstream is higher than its rate at the downstream. Values of predicted and observed pore water pressure are approximately coincident at the depth of 33 m

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