Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 2, No. 8, August, 2016

Prediction of Hydro-mechanical Stability of Dam: Using Calibrated Model from Back Analysis and Monitoring Data

Samad Narimani [a*], Seyed Morteza Davarpanah [b], Javad Sattarvand [c]

[a] *MSc of Rock Mechanic, Sahand University of Technology, Tabriz, Iran*

[b] *MSc of Rock Mechanic, Sahand University of Technology, Tabriz, Iran*

[c] *Assistant Professor, Faculty of Minning Engineering, University of Nevada, Reno, Nevada, USA*

Received 10 July 2016; Accepted 30 August 2016

Abstract

Earth-fill dam safety and stability control during service period is important at the view point of economics and social security. Monitoring is very important to control dam security, to compare real action with predicted planning and to make good experience and opportunity for future planning. In this paper, water pore pressure and settlements in different parts of Sattarkhan dam during service period was studied. So at first, according to instrument data installed in the body of dam, calibration of numerical model done and by doing back analysis real properties of materials of dam defined. Then by using the calibrated model, pore water pressures and settlements of dam studied. Analysis carried out by Flac2D Finite Difference software. The constitutive model used was Mohr-Coulomb at the state of plane strain. Results showed that dam will be safe during service period at the view point of hydro-mechanical behaviour. Finally, stability of dam studied from the view of rapid depletion of the reservoir, which results showed safety conditions.

Keywords: Sattarkhan Dam; Monitoring; Finite Difference; Back Analysis; Rapid Depletion.

1. Introduction

Nowadays, water supply is one of the most important problems in many countries, particularly in Iran which has an arid and semi-arid climatic condition. Consequently the limitation of water resources in Iran has caused the need for implementation of methods for acquiring maximum efficiency from the existing and new water supply projects. To supply the human need for water is considered as one of the most serious problems of mankind, for which a variety of methods are used to provide viable solutions. One of these methods is to build dams, which are locations to store water efficiently; therefore monitoring the behavior of embankment dams in view of the special characteristic of soil which in fact is made of the three basic elements, soil, water & air is very important.

Nowadays, utilizing instrumentations in Dams is more common and help safety and stability control of dams. Also, using back analysis techniques due to results of dam instrumentations are more important in studying of dam behavior. Alireza Farivar et al in 2010, did Back Analysis on Tabarakabad dam in which reached the 16 percent difference error of pore water pressure and 28 percent difference error of settlement between instrument results and numerical modelling. Also Back Analysis results of Maroon dam done by Masoud Pelasi et al in 2010, showed 33 percent difference error of pore water pressure and 6 percent difference error of settlement. Omid Khamesi et al. in 2010 reached 13 percent difference error of pore water pressure between instruments recorded results and calculated results of back analysis techniques. Also Ozkan et al in 2006, recorded 53 percent maximum difference error of pore water pressure in Kurtun Dam [1-4]. Vassilis Gikas et al in 2008 showed that the difference between the vertical displacements predicted by the finite element model and monitoring results at cross section locations adopted in the analysis for the entire lifetime of the Mornos earth dam (Greece) and for the period for which monitoring data, is more

* Corresponding author: samad.narimani65@gmail.com

than 0.03 centimeters [12]. According to the researches that Zhou et al. done on the settlement of Shuibuya dam in 2011, difference between the vertical displacement predicted by the finite element model and monitoring data during the three years of operation is about 5cm [13]. Also as Liang Pei et al showed in 2016, the average absolute value of the relative error between the calculated settlements determined from the back analyzed parameters and the measured settlement is 6.8 percent [14].

2. Outline of Sattarkhan Embankment Dam and Layout of Monitoring Instruments

Supply the downstream agricultural regions. Sattarkhan dam was impounded in 1997 and the dam body civil works finished in 1999; core materials classification were CL to SC soils and materials used in body of dam were GP. The foundation and abutment of the dam consist of Andesite (central and left abutment) and alternation of Andesite and tuff (right abutment). Section of embankment of dam on the alluvial foundation shown in Figure 1. Also general features of the dam are as follows:

Type of dam	: Earth– Rockfill with vertical core
Crest length (m)	: 350
Crest width (m)	:11
Height of dam from foundation (m)	:72
Reservoir volume (106 m^3)	:130
Normal water level (MASL)	:1451

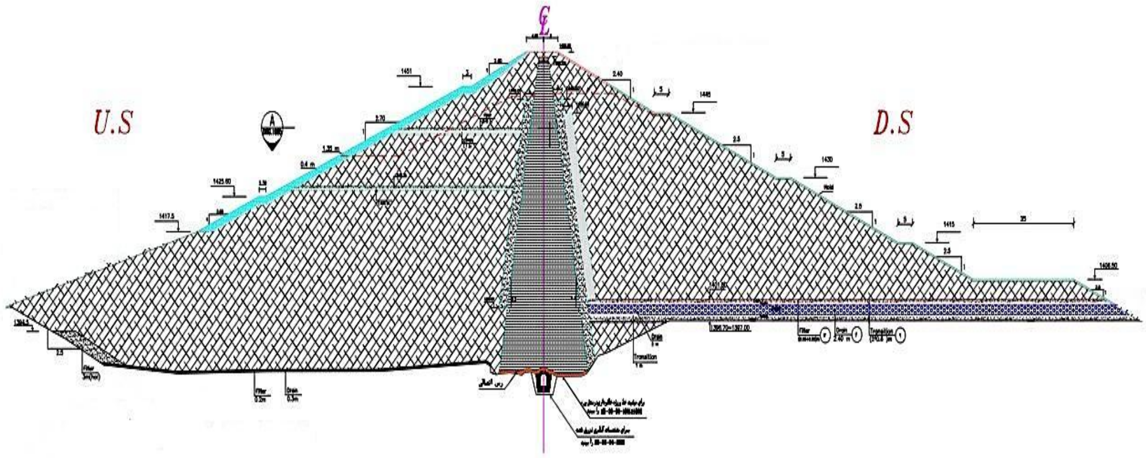


Figure 1. Section of embankment of dam on the alluvial foundation.

In order to control the behavior and response of Sattarkhan dam a monitoring system was designed based on the specification of; dam body, geotechnical conditions of the foundation and the location of the impervious element. Also the layout of the instrumentation was designed to provide easy access for control and taking readings. In view of the conditions of the foundation, the dimensions and geometry of the dam body six monitoring instrumentation sections were designed. A typical instrumentation layout is shown in Figure 2 which is the most critical section of the dam [5].

3. Numerical Modeling

Numerical modelling of Sattarkhan dam was made by FLAC^{2D} in network with total measures of 350×112 meters (see Figure 3).

Boundary conditions were made at corner and bottom artificial boundary, and different parts of dam modeled by making different sections in numerical network. Mohr-coulomb Elasto-plastic constitutive model used for modelling of materials in dams foundation and body. Due to geotechnical studies, primarily values assumed for physical and mechanical parameters of materials which are shown briefly in Table 1.

In order to accurate modelling of in-situ stresses in foundation and body of dam, for accurate modelling of in-situ stresses in dams foundation and body, at first, foundation of dam made and then by applying density and gravity acceleration, initial equilibrium of stresses was established. In the next step, materials of dam body were established step by step and layer by layer. Before adding next layer, stresses equilibrium condition was established. With this method, sudden shocks caused by incurring sudden dam’s body weight, provided. At the end of this process, model of foundation and body of dam prepared for the next analysis, which hydraulic condition of dewatering of the reservoir could be applied [6].

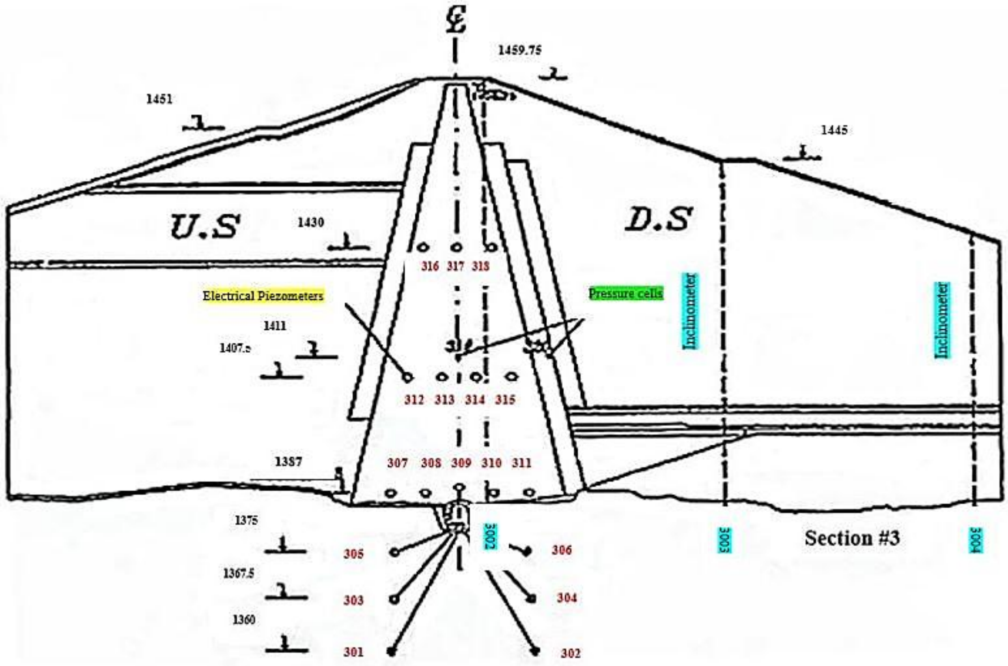


Figure 2. Maximum Instrumentation cross – section of Sattarkhan dam [7]

Table 1. Values of materials used in Sattarkhan Dam [5]

Parts	Density (KN/m^3)	Frictional Angle (degree)	Cohesion (KPa)	Elasticity Module (Kg/cm^2)	Poisson Ratio	Permeability Index (m/s)
Core	20.6	25	30	200	0.35	10^{-7}
Shell	22	40	0	100	0.3	10^{-3}
Filter	22	35	0	250	0.3	2×10^{-4}
Drainage & Transition	22	35	0	500	0.3	3×10^{-3}
Alluvium	22	25	100	500	0.3	5×10^{-3}

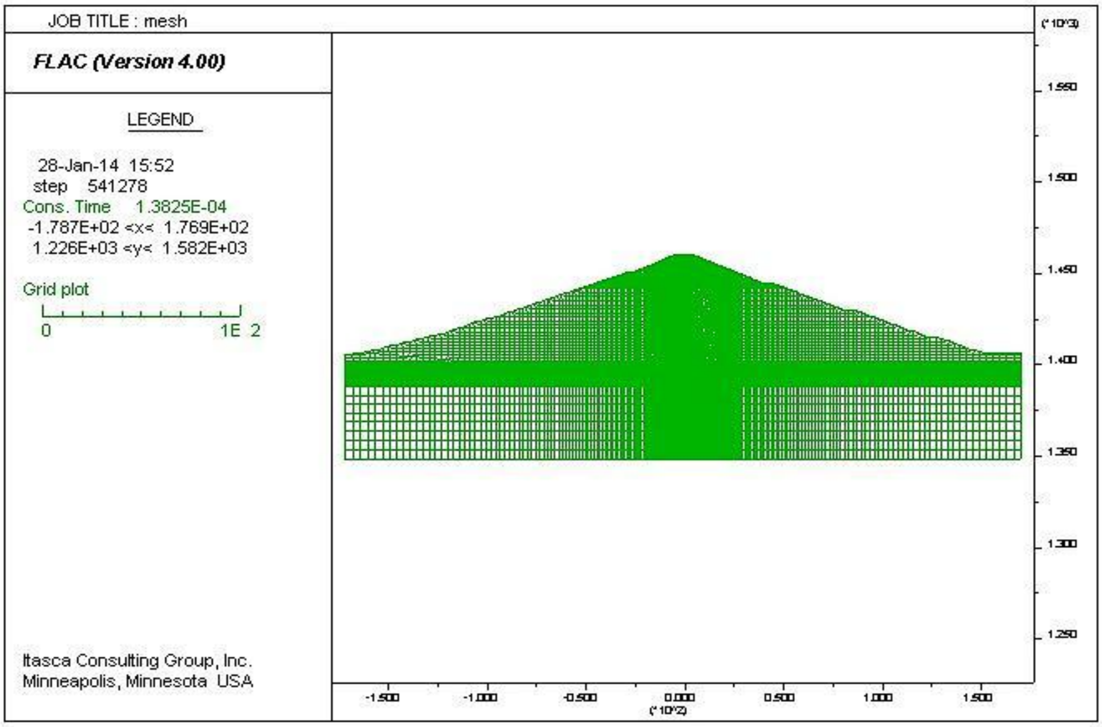


Figure 3. Geometry of Sattarkhan Dam in FLAC^{2D}

4. Back Analysis

The purpose of back analysis techniques is to derive unknown geotechnical parameters, system geometry and boundary or initial conditions based on a limited number of laboratory or in situ measured values of some key variables such as displacements, strains and stresses, using either least square or mathematical programming techniques of error minimization. In figure 4 shown the comparison between normal and back analysis.

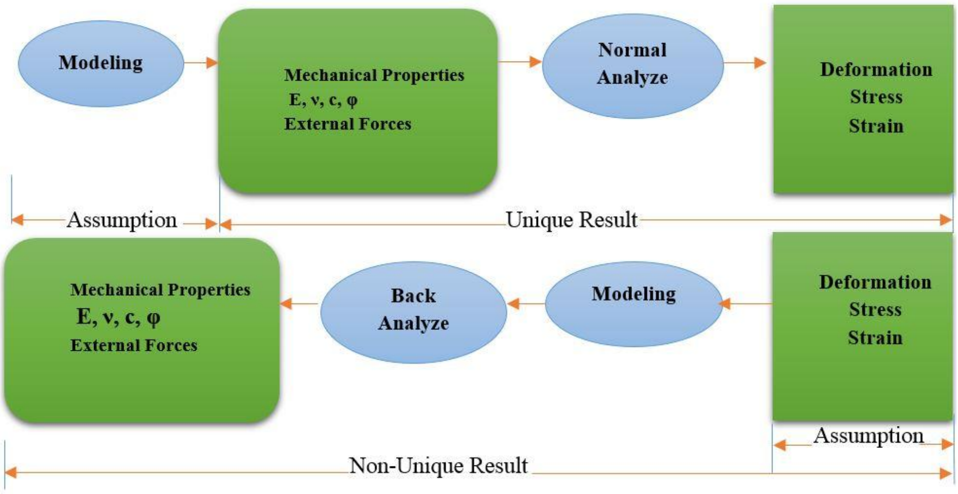


Figure 4. Comparison between normal and back analysis

For doing back analysis, based on results of installed instruments on structure, internal parameters of numerical modelling adjusted, so, results of numerical modelling will matched to those recorded by instruments. In these conditions, behavior of numerical modelling will be consisted with real one [8].

Instruments of 3rd section of dam in the period of first nine months of 2011 used to do back analysis and calibration of numerical modelling. Characteristic of piezometers and their data are shown in Table 2. Due to changing of water head of the reservoir in mentioned period, Calibration of numerical modelling done in three cases: the lowest water head of the reservoir (1437.1), average head (1440.9) and highest head (1442). Recorded data of piezometers in these three heads mentioned in Table 2.

Discrepancy between measured and computed value of pore water pressure is expressed as the error function [15]:

$$(Error)\% = \frac{|U_{piezo} - U_{model}|}{|U_{piezo}|} \times 100 \qquad (1)$$

Where U_{piezo} is measured pore water pressure by piezometer and U_{model} is computed pore water pressure by modelling.

Relative error of each piezometer separately is calculated by equation 1. Also average error at each stage of model can be calculated by Equation 2:

$$(Mean\ Error)\% = \frac{\sum_{i=1}^{n}(Error)_i}{n} \qquad (2)$$

Due to the water head of reservoir, back analysis started by applying hydraulic boundary conditions at upstream of dam. Pore water pressure at installed point of piezometers computed by hydro-mechanical analysis. Generally, computed values are different with those showed in Table 2. But these discrepancies could be reduced by changing the permeability values of different parts of dam. As the discrepancy between measured and computed values is minimum, error obtained with Equations 1 and 2 will be minimum too. With numerous studies, optimal condition determined and the permeability coefficients of different parts of dam obtained as shown in Table 3. Also computed pore water pressures of calibrated model and relative errors are given in Table 4. Error values of each piezometer of calibrated models at max head, average head and min head of reservoir are shown in Graphs of Figure 5. respectively. Also pore water pressure distributions in dam at these models are shown in Figure 6. According to this figure, distribution of pore water pressures in the body and foundation of dam and values of pore water pressure in different parts were acceptable and showed the safe hydraulic condition for the dam.

Table 2. Data used in back analysis [7]

Piezometer No	Install level (m)	U_{p-max} (KPa)	U_{p-min} (KPa)	U_{p-ave} (KPa)
304	1367.5	76.1	80.7	85.2
307	1387	359.8	360	364
309	1387	325.44	323	320
312	1407.5	225.01	224	226
313	1407.5	187.6	185	183

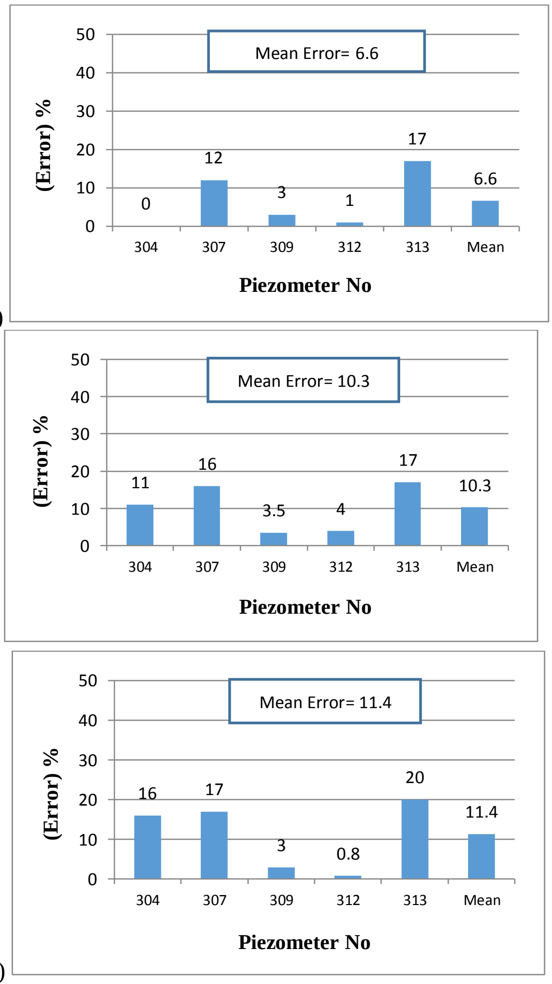
U_{p-max}: measured pore pressure at the highest head of reservoir
U_{p-min}: measured pore pressure at the lowest head of reservoir
U_{p-ave}: measured pore pressure at the average head of reservoir

Table 3. Permeability coefficients from back analysis

Part	Core	Shell	Filter	Drainage	Alluvium	foundation
Permeability	7×10^{-7}	9×10^{-4}	7×10^{-5}	5×10^{-4}	8×10^{-3}	5×10^{-7}

Table 4. Pore water pressure values in numerical model and their errors

Piezometer No	Level (m)	U_{M-max} (KPa)	$(Error)_{max}$ (%)	U_{M-min} (KPa)	$(Error)_{min}$ (%)	U_{M-ave} (KPa)	$(Error)_{ave}$ (%)
304	1367.5	76.1	0	677.5	16	75	11
307	1387	315	12	298	17	306	16
309	1387	314.7	3	313	3	308	3.5
312	1407.5	222	1	225	0.8	216	4
313	1407.5	220	17	222	20	214	17
		$(Mean\ Error)_{max}$:	6.6	$(Mean\ Error)_{min}$:	11.4	$(Mean\ Error)_{ave}$:	10.3

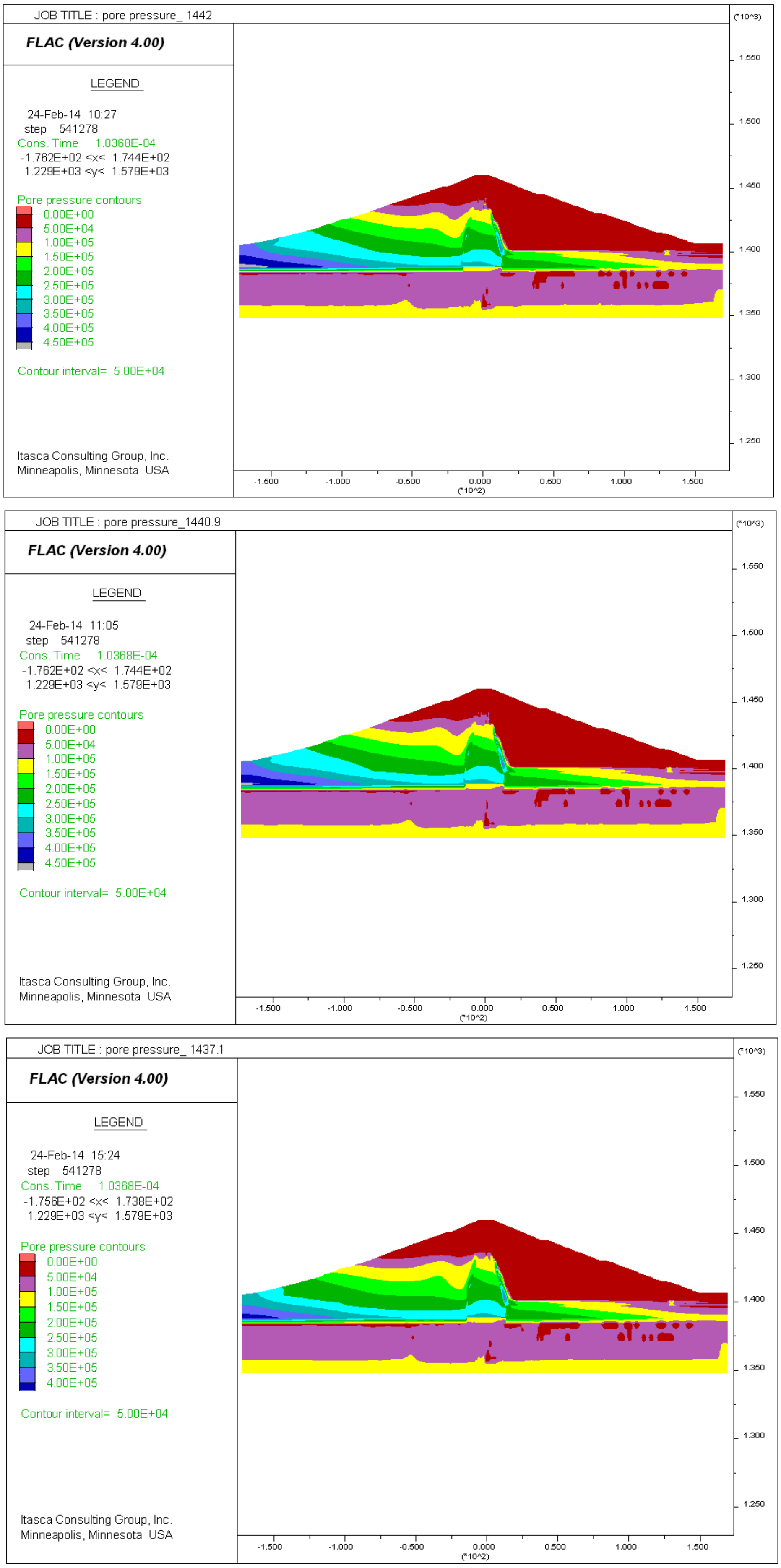


(Maximum head)

(Average head)

(Minimum head)

Figure 5. Piezometers Error values of back analysis for max head, average head and min head, respectively



(Maximum head)

(Average head)

(Minimum head)

Figure 6. Pore water pressure distribution for max head, average head and min head, respectively

Figures 7a to 7c showed the discrepancy of piezometric pressure in foundation, border of foundation and core, and middle of the core at the operation stage which resulted from instruments and back analysis. According to these graphs, values of reached pore water pressure from instruments and back analysis had a pretty adaption with each other.

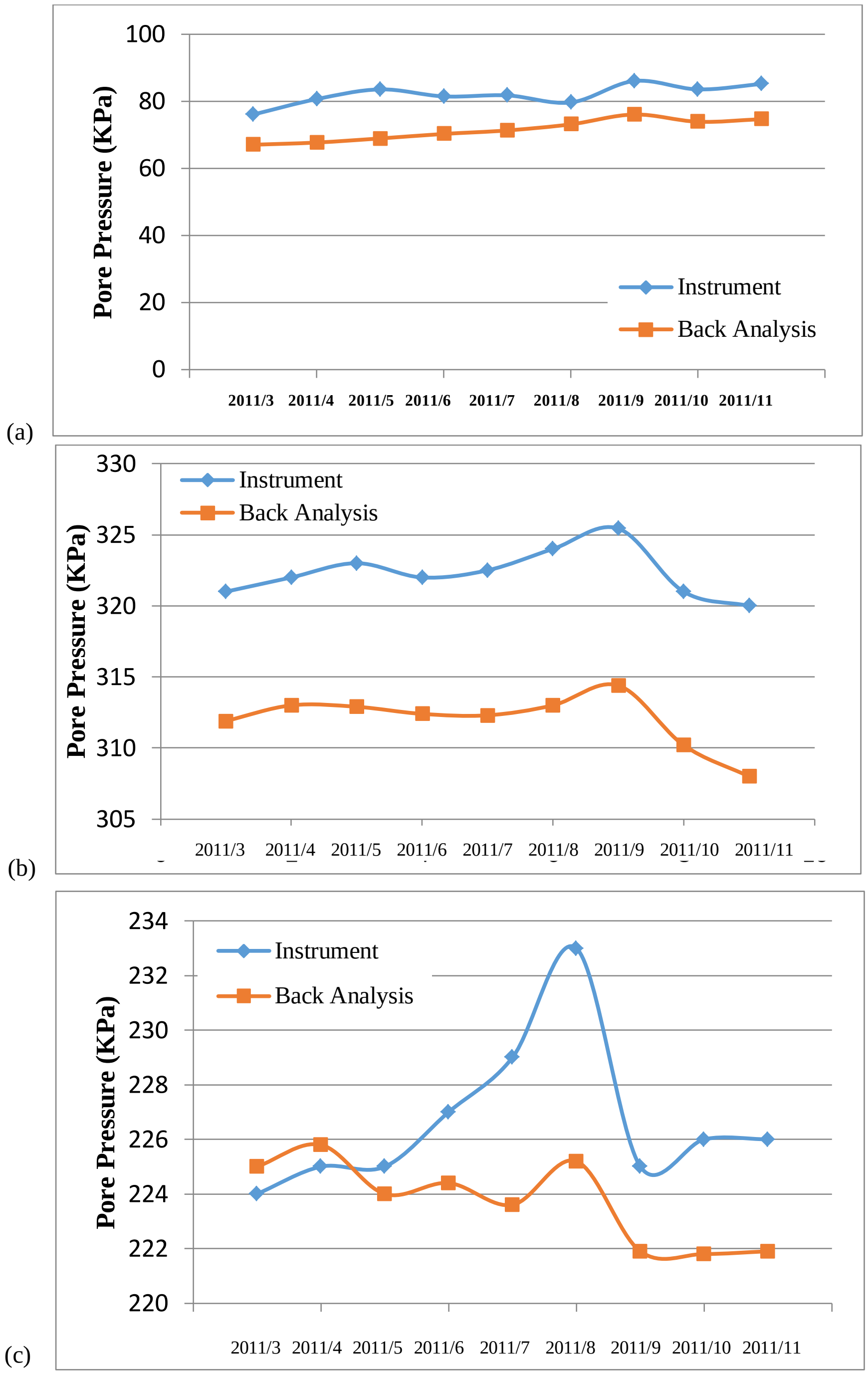


Figure 7. Discrepancy of pore water pressure resulted from instruments and back analysis in (a) foundation, (b) border of foundation and core, (c) middle of core

5. Deformation of Dam Body

Measuring deformation of body of Sattarkhan dam in different parts done by inclinometer tubes and extensometer plates. 12 inclinometers installed in 4 instrumentation profiles. In order to measure the vertical settlements, 200 extensometer plates installed in different levels of these tubes. In Table 5. described the features of inclinometers installed in section 3 [7]. In the first stage of back analysis, pore water pressure of dam matched with the model and next by changing the hardening properties of soil, tried to adopt vertical deformations to model. Back analysis started with applying mechanical boundary conditions of dam body considering to water head of the reservoir of dam. Core settlement in installed point of magnetic plate of borehole, computed by hydro-mechanical analysis. But the discrepancy between measured and computed values could be decreased by changing mechanical properties of materials in different parts of dam.

Table 5. Features of inclinometers installed in section 3

Set Index	Installation position relative to the dam axis (m)	Level of base magnet (m)	Level of cap (m)	Date of the first reading
3002	4.76 D/S	1385.338	1459.945	**Nov. 1998**
3003	39.21 D/S	1385.200	1445.24	**Feb. 1998**
3004	75/38 D/S	1386.430	1432.591	**Nov. 1998**

Final properties obtained from trial and error test and back analysis, shown in Table 6. Considering to the results from back analysis and measured data of inclinometer 3002, settlements resulted from back analysis of sattarkhan dam at the operation phase shown in Figure 8. According to this figure, maximum settlement occurs in core. Also the reason for the high discrepancy between measured and computed values at low levels of the reservoir, could be high resistance of materials at those levels.

6. Stability analysis of sattarkhan dam

The order of dam's stability is that maintaining equilibrium and prevents moving of parts of dam against incoming forces. In other words, dam will be in safe and stable case, if resultant of applied stresses on dam is less than mobilized resistance. Therefore, in designing of dams, there used a criterion which called safety factor, that how much it is greater so stability will be in fine case [9].

6.1. Calculating the Safety Factor of Sattarkhan Dam

In studying stability of embankment dams, usually safety factor considered 1.5. Different engineering organizations in the world, presented logical values as safety factor for assessing the stability of embankment dams in different conditions (see Table 7.) [10].

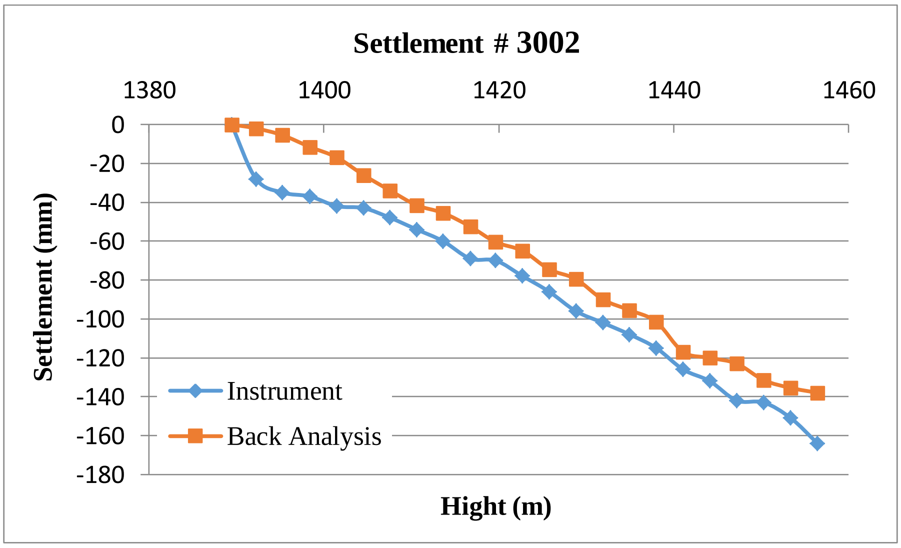


Figure 8. Settlement graph of instruments and calibrated model in core

Table 6. Values of mechanical properties from back analysis

Parts	Density (KN/m^3)	Frictional Angle (degree)	Cohesion (KPa)	Elasticity Module (Kg/cm^2)	Poisson Ratio
Core	19.5	27	40	150	0.4
Shell	21	42	0	850	0.25
Filter	21	37	0	200	0.25
Drainage	21	37	0	350	0.25
Alluvium	21	28	20	350	0.25
Foundation	25	30	200	100000	0.25

Table 7. Minimum safety factor in embankment dams stability analysis [10]

Stability Analysis Conditions	Upstream		downstream	
	No Earthquake	Earthquake	No Earthquake	Earthquake
End of Construction	1.25	1.0	1.25	1.0
Permanent leakage, Half Full Reservoir	1.5	1.25	-	-
Permanent leakage, Full Reservoir	-	-	1.5	1.25
Rapid Depletion of Water	1.25	1.0	-	-

After determining the real properties of the dam materials, safety factor of dam at the end of construction calculated by calibrated model. By using $FLAC^{2D}$, safety factor was 1.91 which would be suitable value for the end of the construction phase (see Figure 9).
Also safety factor values for maximum level, average level and minimum level of operation phase presented in Table 8. which are suitable values.

Table 8. Safety Factor Values of Operation Phase

Water Head Level (m)	Safety Factor
1442	1.86
1440.9	1.90
1437.1	1.91

One of most important factor for assessing pore pressure is determining maximum pore water pressure index which is defined as below [11]:

$$(R_u)_{max} = (u/\gamma h)_{max} \quad (3)$$

Where $(Ru)_{max}$ is maximum pore water pressure index (KPa), u is pore water pressure (KPa), γ is soil density (KN/m^3) and h is the height of embankment.
Maximum pore water pressure index for maximum, average and minimum water head of monitoring results and modelling shown in Table 8. How much this index was less than one, hydraulic stability of dam would be in proper case. So, due to results showed in Table 9, maximum pore water pressure index values showed that Sattarkhan dam was in proper case.

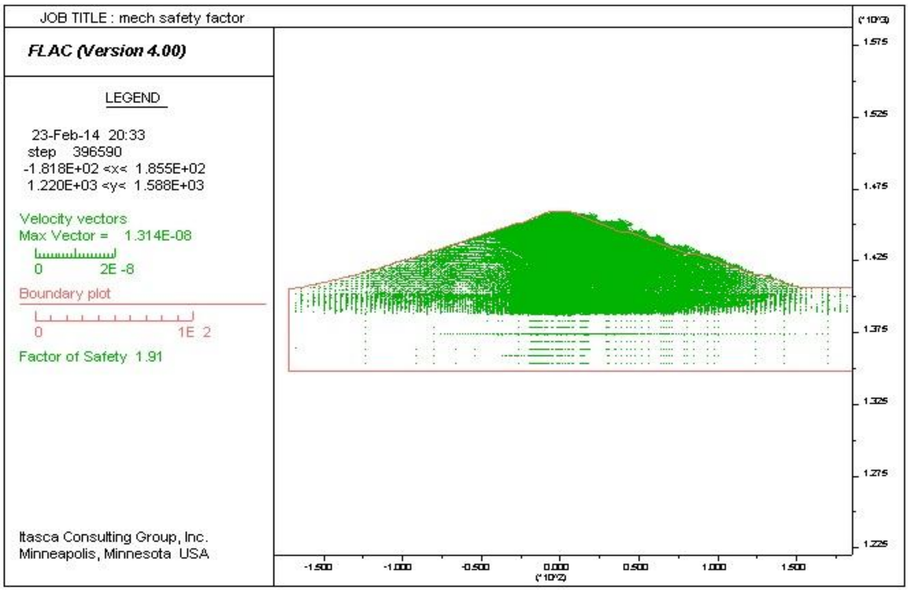


Figure 9. Safety factor calculation in the end of dam construction

Table 9. Maximum pore water pressure index values from monitoring and modelling

Water Head (m)	Maximum pore water pressure index (monitoring)	Maximum pore water pressure index (modelling)	Error (%)
1442	0.49	0.43	12
1440.9	0.48	0.42	12
1437.1	0.49	0.43	12

6.2. Rapid Depletion of Reservoir during Operation Phase

When rapid depletion occurs, water level in front of slope reduces rapidly. This condition particularly occurs in dams. Failures caused by rapid depletion, often occur on slopes formed of clay materials. Because pore water pressure has not enough time to be vanished and then total shear resistance is reduced.

To study stability of Sattarkhan dam when rapid depletion occurs, dam's normal head considered as primary head and defined its water table. Then selected four water levels and water table of these four level drawn based on water table of dam's normal water table, and eventually safety factors determined for these four levels (see Table 10).

Table 10. Safety Factors in Rapid Depletion

Reservoir level after droption (m)	Safety Factor
1425	1.26
1420	1.28
1415	1.31
1410	1.33

7. Conclusion

Stability of Sattarkhan dam during the operation phase studied in this paper. Flac program was used for numerical analysing. Due to back analysis and instrument data, properties of materials of Sattarkhan dam revised somewhat. At the end attention should be taken to following items:

- Studying the pore pressure in foundation and core showed that real pore water pressure and back analysis results were matched together.
- Most recorded and computed settlements occurred at downstream of the dam were 17 and 14 centimetres respectively. The main reason for this discrepancy could be a lower deformation module of core than the shell of dam.
- Computed safety factor at the end of construction were 1.91 and at the operation phase at maximum, average and minimum water levels of reservoir were 1.86, 1.90 and 1.91 respectively.
- By analysing the numerical modelling of dam at the normal head (1451 m), pore water pressure distribution and water table of dam determined. Then safety factors determined for rapid depletion of reservoir in different water levels. So results showed safety conditions for dam.

So by comparing the results of this research to others as discussed before, it is distinctive that results from back analysis and monitoring data have a suitable conformity. Whereas most researches which done by other researchers on analogous dams have had less conformity among the numerical results and monitoring data.

8. Acknowledgment

Author is grateful to Power Ministry of Iran (East Azerbaijan Province Regional Water Company) specially Eng. Mohammad Reza Mohammadi for their help in providing the instrument reading in Sattarkhan dam.

9. References

[1] A. Farivar and A. Mirgasemi, "studying behavior of Tabarak Abad Dam During Construction by Using Back Analysis," Civil Engineering Journal of Tehran University (2010) vol. 3: 407-412.

[2] O. Khamesi and A. Mirgasemi, "studying Hydraulic Fracture in the core of earth-fill dams," Civil Engineering Journal of Tehran University (2010) vol. 2: 181-191.

[3] S. Ozkuzukiran, M. Y. Ozkan, and M. Ozyazicioglu, "Settlement behaviour of a concrete faced rock-fill dam," Journal of Geotechnical and Geological Engineering (2006) vol. 24: 1665–1678.

[4] M. Pelasi and B. Salehi, "studying behavior of Maroon Dam During operation phase by Using Back Analysis," Civil Engineering Journal of Tehran University (2010) vol. 5: 607-619.

[5] "Geological Report of Sattarkhan Dam," Band Ab Consulting Engineering Co, Power Ministry of Iran1997.

[6] "Fast Lagrangian Analysis of Continua, Manual," ed. Minneapolis, Minnesota: Itasca Consulting group, Inc, 2002.

[7] "Instrumentation Report of Sattarkhan Dam," Band Ab Consulting Engineering Co, Power Ministry of Iran2011.

[8] M. Ghorbani, M. Sharifzade, and R. Masoudi, "Back analysis techniques in geotechnical engineering," Amirkabir Civil Journal, 2009.

[9] B. M. Das, Principles of Geotechnical Engineering. USA: University of Texas, 1994.

[10] USCE, Stability of Earth and Rock-fill Dam. USA: US. Department of Army, Corps of Engineering, 1997.

[11] F. Robin and M. Groger, Geotechnical Engineering of Embankment Dams. USA: Balkema, 1992.

[12] Vassilis Gikas, Michael Sakellariou, "Settlement analysis of the Mornos earth dam (Greece): Evidence from numerical modeling and geodetic monitoring," Journal of Engineering Structures (2008) vol. 30: 3074-3081.

[13] Wei Zhou, Junjie Hua, Xiaolin Chang, Chuangbing Zhou, "Settlement analysis of the shuibuya concrete-face rockfill dam ," Journal of Computers and Geotechnics (2011) vol. 38: 269-280.

[14] Qinqin Guo, Liang Pei, "Response surface and genetic method of deformation back analysis for high core rockfill dams," Journal of Computers and Geotechnics (2016) vol. 74: 132-140.

[15] S. M. Davarpanah, M. Sharifzadeh, J. Sattarvand, S. Narimani, "Evaluation of building displacement induced by EPB tunneling through GPS-GNSS monitoring system and back analysis technique (Tabriz subway tunnels),"Civil Engineering Journal" (2016) vol. 2: 270-285.