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PREDICTING DOROODZAN DAM HYDRAULIC BEHAVIOR DURING RAPID DRAWDOWN*

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Abstract– Doroodzan dam is a 57m high earth dam with rip-rap cover constructed on Kor River in Bakhtegan Basin. The dam is located at 30° 12' 2" north latitude and 52°25' 5" east longitude ~70km north of Shiraz, Iran. The dam reservoir supports a large amount of agricultural, industrial, and urban demands in the region. The reservoir volume is 993 M.C.M at the normal pool level and the dam crest length is ~700m. In this paper, a 3-D finite element model of the dam was constructed and analyzed for steady and transient conditions. Transient pore water pressure fluctuations were predicted at different piezometer locations for a 21-day rapid drawdown of 23.9m. It was found that seepage through the dam is not sensitive to hydraulic conductivity of downstream dam body, apparently due to the effective hydraulic behavior of the chimney drainage there. Under rapid drown down conditions, a maximum of 11.8m excess pore water pressure on upstream part of the dam was observed (compared to the steady state conditions) while no significant excess pressure was seen at the downstream part of the dam. Dynamics of the phreatic line location during the 21-day rapid drawdown was monitored in four 5.25-day time steps. A gradual phreatic line change at time steps ending at the 21-day period was predicted. Phreatic line at the upstream face of the dam closely followed the reservoir level rapid drawdown. However, phreatic line at the interior sections of the dam did not drop as fast. As a result, a gradient towards upstream face of the dam was developed after ~10 days which might jeopardize slope stability there. It is recommended that the excess pore water pressure be carefully considered in dam analysis researches, especially during the transient periods. In general, rapid drawdown should be cautiously analyzed in dams, especially those with short emptying times, as it may reverse the seepage direction, endanger the slope stability, and not allow excess pore water pressure to dissipate in an acceptable manner.

Keywords– Doroodzan dam, rapid drawdown, pore water pressure, transient analysis, hydraulic behavior

1. INTRODUCTION

Reservoir dams are usually considered as the main suppliers of water for drinking, industrial, and agricultural purposes. They also serve as a major flood control system and often supply water to power plants. Consequently, dams' stability and safety play a vital role, especially at critical times such as flood periods. Pore water pressure and flow analysis are among critical indicators of the proper hydraulic behavior in earth dams [1]. Dangerous phenomenon such as piping and slope instability are extremely affected by excess pore water pressures [2]. Piezometers are common devices for displaying pore water pressure fluctuations in earth dams [3]. Their readings may reflect the hydraulic behavior of different parts of a dam such as its body, core, and/or foundation.

Pore water pressure in earth dams may be analyzed under steady or transient conditions. Analysis of dam hydraulic behavior, slope stability, and safety factor during rapid drawdown of reservoir water level

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is usually performed using numerical models under transient conditions with proper initial and boundary conditions. Experiments of seepage flow through dams with unsteady conditions conducted in laboratory by researchers confirm the reliability and accuracy of numerical models for predicting pore pressure heads in the dam body. Furthermore, recent studies show excellent capability of finite element models and artificial neural networks for predicting pore pressure during rapid drawdown [4~9]. 3-D transient analyses under such critical conditions are usually needed because of in-situ flow complexities and problems such as incorrect seepage analysis in the case of anisotropic materials, associated with 2-D flow analyses [10]. Unsaturated zone has a considerable effect on slope stability, safety factor, and deformation of dams [7, 8], however, it does not change overall flow conditions and hydraulic behavior of the dam considerably [11]. It is believed that classical concept of a free surface is not always applicable when dealing with transient seepage through soils [12].

In this research, a 3-D finite element model was constructed to predict Doroodzan Dam hydraulic behavior during rapid drawdown. Seep 3D software, produced by GEO-SLOPE, was used for the analyses [13,14]. Steady and transient conditions with proper initial and boundary conditions were performed. A 4-year period (1999 to 2002) data of 14 piezometers in Doroodzan Dam were used for calibrating the model, and the results were verified via piezometer observations during a 5 month period in 2005 [15,16]. Saturated and unsaturated hydraulic conductivities of different materials used in the dam body were used as calibration parameters.

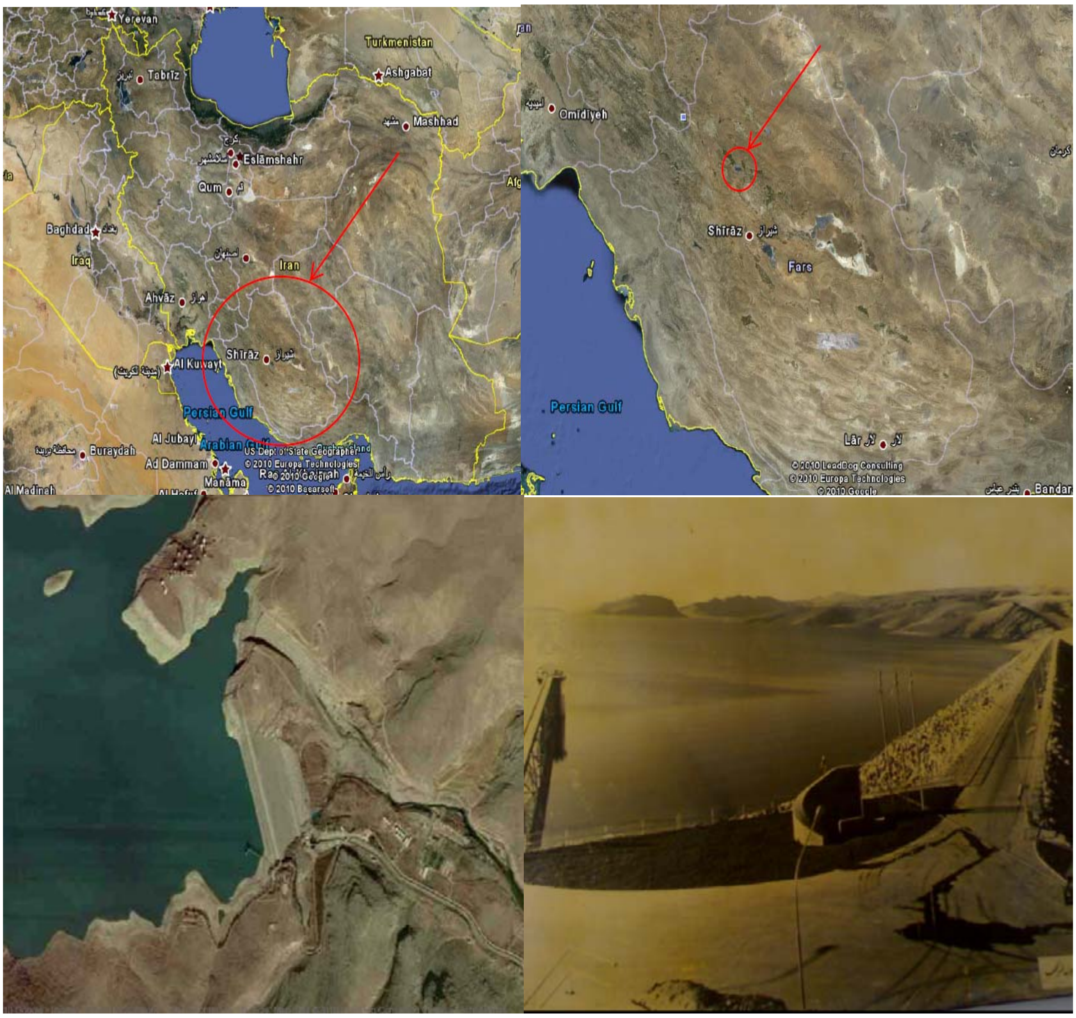


Fig. 1. Doroodzan dam satellite and crest views

2. DAM CHARACTERISTICS

Doroodzan dam was constructed on Kor river between 1978-1982 with the aims of Korbal plain irrigation, Shiraz and Marvdasht drinking water supply, provision of petrochemical complex water demand, production of electricity (with 10 MW capacity) and winter flood control. The dam is constructed on an open 350m wide U shaped valley. Dam material includes body material at upstream and downstream, drainage material, rip-rap cover at upstream, foundation material and cut off wall material under dam body. It has a central, vertical, and three 10m wide horizontal drainage galleries (chimneys). Height of the dam is 57m above river bed with a 700m long 6m wide crest. Normal reservoir level is at 1676.5m and the crest level is at 1683.5m above mean sea level. Total reservoir volume is 993 MCM with an 860 MCM effective volume. Rapid drawdown limit is 23.9m. Dam spillway is a free arch ogee spillway with an entrance height of 4m and a length of 150m which rests on the left support with a chute and unlined downstream canal (Fig. 2).

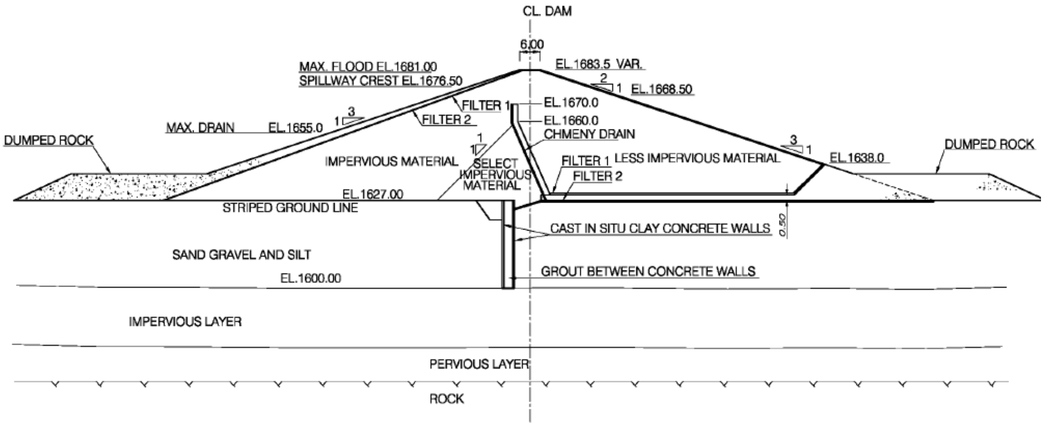


Fig. 2. Cross Section A-A of Doroodzan Dam (the cross section is shown on Fig. 4)

29 hydraulic and 22 vertical piezometers installed in the body and foundation of Doroodzan dam are used to monitor pore water pressures. During the dam operation some piezometers were not working properly and as a result 14 extra vertical piezometers were installed in the dam. Figure 3 shows the location of piezometers installed in the dam. In this study, observed piezometric heads in three selected piezometers (NP1, NP5, and NP6), installed at the bottom of dam body, were collected from Water Organization of Fars Province and used for model calibration and verification.

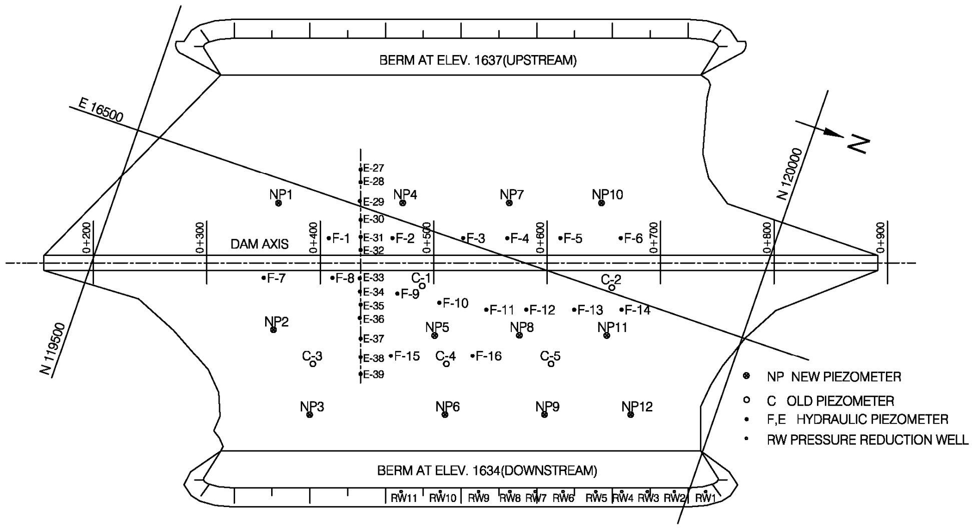


Fig. 3. A plan view of piezometers location in Doroodzan dam

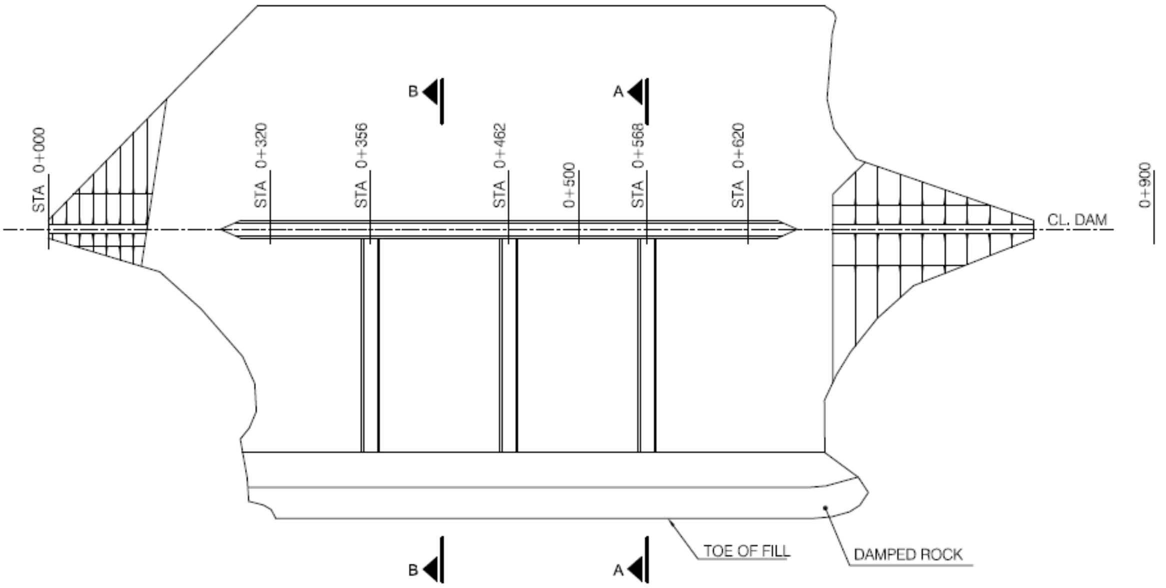
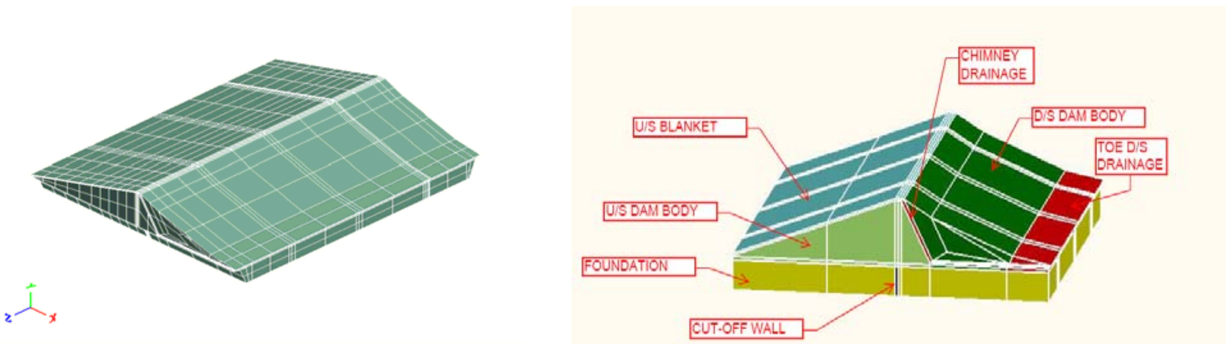


Fig. 4. Doroodzan dam horizontal and vertical drainage locations

3. MODELING

A 3-D finite element model of Doroodzan dam was made in Seep 3D (Fig. 5). The selected grid (shown on the figure) was used based on effective (optimum) computational time required for the dam analysis. Smaller grids took too long a time for analysis (more than 20 min for each run) without any significant improvement in the results. Transient seepage analysis was performed for a period of 975 days during 1999-2002. Figure 6 shows reservoir and piezometric level observations during this period which were used as data for calibration of the model. As shown on the figure, piezometers located on the upstream part of the dam (NP1, NP4, NP7, and NP10) follow the reservoir level fluctuations very closely. It reflects minimal resistance of upstream material which separates the mentioned piezometers from the reservoir**.** Upstream boundary condition for model calibration and verification was "specified head" (i. e. the reservoir level) for different conditions. Boundary condition above the water level, near the crest, was set as a potential seepage face. Downstream boundary condition was set as a "potential seepage face" on the dam downstream and foundation. For the bottom of the foundation, however, "no flux" was considered.



(a) (b)

Fig. 5. (a) Doroodzan dam 3-D finite element model, (b) dam body components

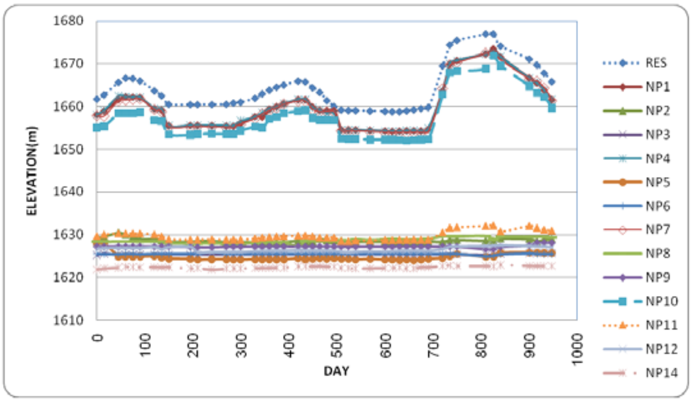


Fig. 6. Reservoir and piezometric level observations used for model calibration

Modeling has been accomplished based on solving the governing equation in porous media as follows:

$$\frac{\partial}{\partial x}(K_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial H}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial H}{\partial z}) + Q = \frac{\partial \theta}{\partial t} \quad (1)$$

where H is hydraulic head [L], K_x, K_y, and K_z are hydraulic conductivities [L/T] in x, y and z directions, respectively. θ is the volumetric water content [L^3L^{-3}], Q is flux per unit volume [$L^3T^{-1}L^{-3}$] added to or withdrawn from the control volume, and t is time [T]. Under steady state conditions the right hand side of equation (1) is zero. Water content may be related to pore water pressure via equation 2, and hence the governing equation may be written in terms of hydraulic head (H) as equation 3:

$$\partial \theta = m_w \partial u \quad (2)$$

$$\frac{\partial}{\partial x}(K_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial H}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial H}{\partial z}) + Q = m_W \gamma_W \frac{\partial (H - z)}{\partial t} \quad (3)$$

m_w is the slope of Soil Water Characteristic Curve (SWCC) at any suction [$M^{-1}LT^2$], u is pore water pressure [$ML^{-1}T^{-2}$], z is elevation head above a datum [L], and γ_W is the unit weight of water [$MT^{-2}L^{-2}$].

4. MODEL CALIBRATION

In order to estimate hydraulic conductivity of various parts of the dam, calibration was accomplished based on minimizing differences between transient simulated and observed hydraulic heads at piezometers NP1, NP5 and NP6. Figure 7 shows observed and transient simulated elevations at piezometers NP1, NP5 and NP6 with different hydraulic conductivities. Table 1 shows statistical analysis results on the differences mentioned above. Average, min, max, and RMSE represent Mean Absolute Error (MAE), minimum absolute error, maximum absolute error, and root mean square error, respectively. Calibrated hydraulic conductivities of the dam materials are summarized in Table 2. Figures 8a) and b) show total head simulated with hydraulic conductivities before and after calibration at two cross sections of the dam. For comparison purposes, observed heads at NP1 and NP5 after *810* days are also shown on the figure**.** As shown, the differences between simulated and observed elevations at the upstream material have considerably improved as a result of calibration such that the maximum difference is less than few meters at this critical reservoir elevation. Figure 8c) shows the model result after calibration when the reservoir is full. It depicts the role of three horizontal drainages in streamline convergence at these locations. Based on the software manual recommendation for sandy soil, coefficient of volume compressibility m_v was set equal to $0.0001\ kpa^{-1}$.

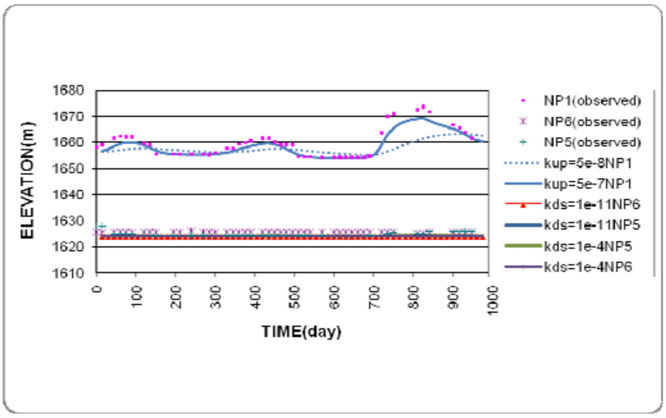
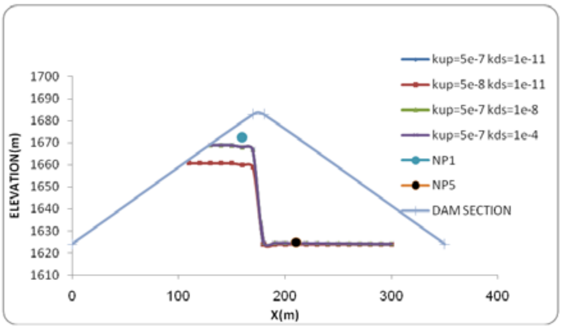
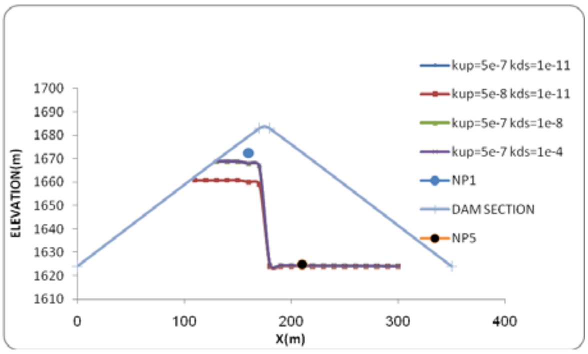


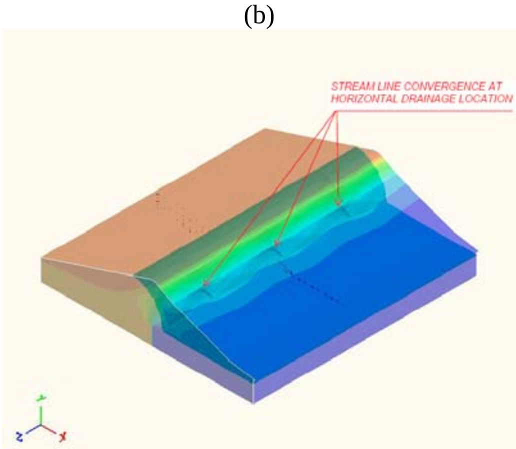
Fig. 7. Observed and simulated elevations at piezometers NP1, NP5, NP6 for two upstream (K_{up}) and two downstream (K_{ds}) hydraulic conductivities (in *m/s*)



(a)



(b)



(c)

Fig. 8. Observed and simulated total head at (a) horizontal drainage location (section A-A on Fig. 4), (b) between horizontal drainages (section B-B on Fig. 4) at t=810 days, and (c) Seep 3D model result showing horizontal drainage performance when the reservoir is full

Table 1. Statistical analysis results for calibration at (a) NP1 and (b) NP5

(a)

	Error (m)			
	Average (MAE)	Max	Min	RMSE
K_{up}=5x10^{-7} (m/s)	1.68	7.17	0.0675	2.27
K_{up}=5x10^{-8} (m/s)	3.72	13.3	0.3378	5.16

(b)

	Error (m)			
	Average (MAE)	Max	Min	RMSE
K_{ds}=1x10^{-4} (m/s)	0.4682	3.691	0.0015	0.65
K_{ds}=1x10^{-11} (m/s)	0.52	3.75	0.00015	0.73

Table 2. Results of hydraulic conductivity calibration for different dam materials

Dam material	Hydraulic Conductivity (*m/s*)
Chimney & horizontal drainage	5×10^{-3}
Upstream dam body	5×10^{-7}
Downstream dam body	1×10^{-11}
Foundation	4.7×10^{-4}

5. MODEL VERIFICATION

Following calibration of the model, transient analysis was performed for a 5-month period in 2005. Fig. 9 shows observed and simulated elevations at NP1 and NP5. As shown on the figure, observed and simulated elevations have small differences, especially at the upstream location (NP1). Based on the errors for verification (shown in Table 3), a maximum of 5.86 m difference at NP5 (downstream material) was observed. The difference was acceptable, considering ambiguity in material property and homogeneity in the 39-year old dam.

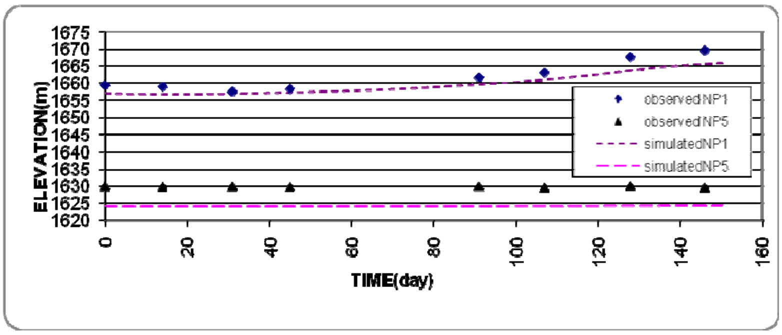


Fig. 9. Verification results based on observed and simulated elevations at NP1 and NP5

Table 3. Statistical analysis results for verification of elevations at two piezometer locations

	Error (m)			
Piezometers	Average (MAE)	Max	Min	RMSE
NP1	2.01	3.58	0.45	2.19
NP5	5.76	5.86	5.55	5.75

6. PREDICTIING THE DAM HYDRAULIC BEHAVIOR DURING RAPID DRAWDOWN

In order to predict the dam hydraulic behavior during rapid drawdown, a transient model of the dam was run and hydraulic head at piezometers NP1, NP5 and NP6 were investigated. Upstream boundary condition was a linear 23.9-m fall of the reservoir level (from elevation 1676.5m to 1652.6m) during a 21-

day period. The reservoir emptying time during the rapid draw down (21 days) was set according to the dam outlet capacity. Figure 10 shows total head variations during rapid drawdown at the dam upstream (NP1) and downstream (NP5 and NP6) locations.

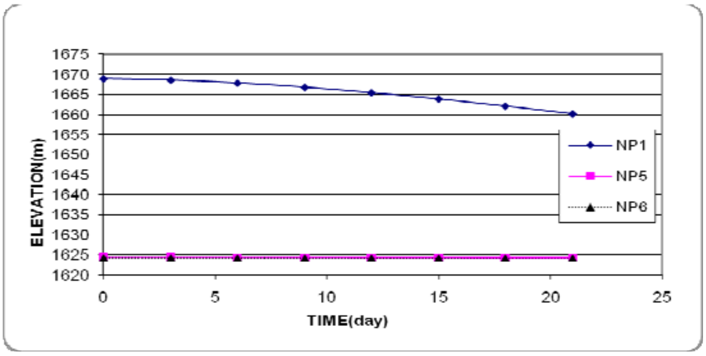


Fig. 10. Total head variation during rapid drawdown at the dam upstream and downstream locations

As shown on the figure, only an 8.7 m decrease in head is predicted at NP1 location (head difference at the beginning and end of rapid drawdown analysis read from the figure as: 1668.92 – 1660.22 = 8.7 m). When compared to the steady state condition of the dam with empty reservoir (with the reservoir level at 1652.6 m producing a head elevation of 1648.42 m at NP1, shown on Fig. 11), an 11.8 m excess head at NP1 is predicted immediately following the dam rapid drawdown (1660.22 – 1648.42 = 11.8 m). The excess pore water pressure has not completely dissipated, apparently due to the lack of sufficient time to reach pore water pressure equilibrium in the dam upstream material. This excess pore water pressure highlights the need for further investigation of upstream face slope stability in conjunction with the dam hydraulic behavior. Such excess heads during rapid drawdown have been observed by other researchers at theoretical and experimental scales [4~8].

As shown on the figure, no significant change is predicted in total head at the dam downstream part at NP5 and NP6 locations. Apparently, the downstream and upstream parts of the dam have independent hydraulic behaviors. It is postulated that the chimney drainage system at the downstream part (with its efficient hydraulic role in dropping the phreatic surface as shown in Fig. 8) maintains the constant head there under transient conditions of rapid drawdown.

Dynamics of the phreatic line location during the 21-day rapid drawdown was monitored in four 5.25-day time steps. Figure 11 shows this location for every time step and for the steady state condition with empty reservoir. The figure reflects a gradual phreatic line change at time steps ending to the 21-day period. As shown on the figure, phreatic line at the upstream face of the dam closely follows the reservoir level rapid drawdown. However, at the interior sections of the dam phreatic line does not drop as fast. As a result, a gradient towards upstream face of the dam is developed after ~10 days which may jeopardize slope stability there.

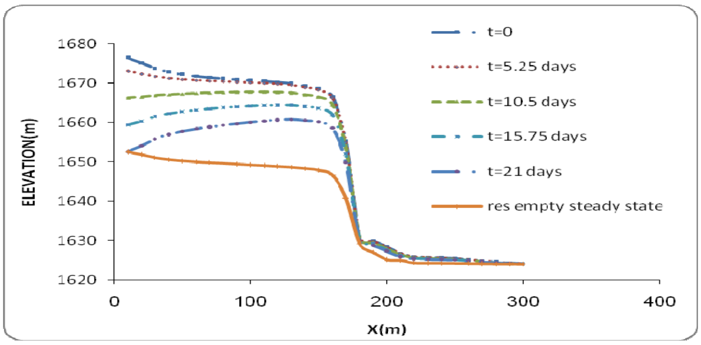


Fig. 11. Phreatic line dynamics during rapid drawdown and at steady state at section A-A

7. CONCLUSION

In this paper, a 3-D finite element model of Doroodzan dam was constructed and analyzed for steady and transient conditions. Transient pore water pressure fluctuations were predicted at different piezometer locations for a 21-day rapid drawdown of 23.9m. It was found that seepage through the dam was not sensitive to hydraulic conductivity of downstream dam body, apparently due to the effective hydraulic behavior of the chimney drainage there. Under rapid drown down conditions, a maximum of 11.8m excess pore water pressure head on upstream part of the dam was observed (compared to the steady state conditions) while no significant excess pressure was seen at the downstream part of the dam. Dynamics of the phreatic line location during the 21-day rapid drawdown was monitored in four 5.25-day time steps. A gradual phreatic line change at time steps ending at the 21-day period was predicted. Phreatic line at the upstream face of the dam closely followed the reservoir level rapid drawdown. However, at the interior sections of the dam phreatic line did not drop as fast. As a result, a gradient towards upstream face of the dam was developed after ~10 days which might jeopardize slope stability there. It is recommended that the excess pore water pressure be carefully considered in dam analysis researches, especially during the transient periods. In general, rapid drawdown should be cautiously analyzed in dams, especially those with short emptying times, as it may reverse the seepage direction, endanger the slope stability, and not allow excess pore water pressure to dissipate in an acceptable manner.

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REFERENCES

1. Kutzner, C. (1997). *Earth and rock fill dams principle and design construction.* Balkema, N.Y.
2. Narita, K., Okumura, T., Kimura, K. & Ohne, Y. (2004). Centrifuge tests on seepage behavior in embankment dam during rapid draw-down. *Proceedings of the 4th International Conference on dam engineering*. Nanjing, China. *Journal of Aichi Institute of Technology*, Japan, pp. 85-90.
3. U.S. Army Corps of Engineers, (1995). Instrumentation of embankment dams and levees engineering manual, EM 1110-2-1908.
4. Shang-jie, X., Fa-ning, D., Oing, H. & Su-zhen, C. (2009). Analysis of stability of dam slope during rapid drawdown of reservoir water level. *International conference on engineering computation*; ICEC, Hong Kong, pp. 221-224.
5. Jia, G. W., Zhan, T. L. T., Chen, Y. M. & Fredlund, D. G. (2009). Performance of a large-scale slope model subjected to rising and lowering water levels. *Journal of Engineering Geology*, Vol. 106, No. 1-2, pp. 92-103.
6. Berilgen M. M. (2007). Investigation of stability of slopes under drawdown conditions. *Journal of Computers and Geotechnics*, Vol. 34, No. 2, pp. 81-91.
7. Huang, M. & Jia, C. (2009). Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage. *Journal of Computers and Geotechnics*, Vol. 36, pp. 93-101.
8. Jun-feng, F. & Sheng, J. (2009). A study on unsteady seepage flow through dams. *Journal of Hydrodynamics*, Vol. 21, No. 4, pp. 499-504.
9. Tayfur, G., Swiatek, D., Wita, A. & Singh, V. (2005). Case study: finite element method and artificial neural network models for flow through jeziorsko earthfill dam in Poland. *Journal of Hydraulic Engineering*, ASCE, pp. 431-440.
10. Jafarzadeh, F. & Shafipour, R. (2003). Three dimensional seepage analysis of earth dams considering valley shape effects. *Proceedings of the 6th International Conference of Civil Engineering*. Isfahan, Iran.

11. Rakhshandehroo, G. & Bagherieh, A. (2006). Three dimensional analysis of seepage in 15-Khordad dam after impoundment. *Iranian Journal of Science and Technology, Transaction B, Engineering,* Vol. 30, No. B1, pp. 55-68.
12. Neuman, S. P. (1973). Saturated-unsaturated seepage by finite elements. *Journal of Hydraulic Engineering*, ASCE, Vol. 99, No. 12, pp. 2233-2250.
13. Geo-Slope, Seep 3D User's manual (2002). Version 5.13.
14. Geo-Slope Seep W User's manual (2002). Version 5.13.
15. Regional Water Organization, Fars Province, Doroodzan dam office data centre. (2009). Shiraz, Iran.
16. Mahab-Ghods Consultant Engineers, Technical Report (1993). Safety evaluation and stability of Doroodzan dam. Tehran, Iran.