Efficiency analysis of seepage of Baz Ali small dam, Kurram Agency using clay blanket and cut-off wall with sand filter

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Abstract: Seepage always eventuates through the foundation of all dams. The flow of water through the dam body generate seepage forces and endanger the dam stability due to piping. Controlling seepage after construction is quite difficult and an expensive job, hence proper practices should be adopted for seepage remediation in the designing stage. In order to investigate the more effective techniques among downstream (D/S) sand filter with upstream (U/S) clay blanket and cut-off wall, the Baz Ali small dam was analyzed using finite element approach SEEP/W 2D. The seepage behaviour through the dam was intuited by employing 1 m thick clay blankets on the upstream side with extending lengths of 50 m, 100 m, 150 m, 200 m, 250 m and 300 m. Furthermore, 5 m, 7.5 m and 10 m deep cut-off walls having 0.5 m and 1 m thickness were embedded for seepage mitigation. The seepage values obtained from SEEP/W 2D models were compared with each other. The SEEP/W 2D results and cost analysis show that clay blanket is more effective and an economical technique than a cut-off wall for tackling seepage issue. Hence, an upstream blanket of 100 m length is more efficient to diminish the seepage up to 58.65% in contrast to the base case without the remedial system.

Keywords: Seepage, D/S sand filter, U/S clay blankets, cost analysis

INTRODUCTION

Seepage is the flow of water through soil under a hydraulic gradient. The hydraulic gradient must exist between two points when changes in hydraulic head occur (Venkatramaiah, 2006). Seepage analysis is vital for civil engineers in designing and construction of dams, barrages, weirs retaining walls and tunnels. The seepage creates forces and quick-sand condition in hydraulic structure, hence maximizes the risk of instability to the structure (Qureshi, 2011). The seepage forces mainly depend on the hydraulic conductivity of soil mass (Chen *et al.*, 2014).

Hydraulic structures such as earthen dams encounter seepage through its foundation or within dam body. The seepage triggered failure occurs when the seepage magnitude exceeds the permissible limits. Property loss, environmental damages and fatalities occur due to dam failures (Ghobadi *et al.*, 2005). On August 4, 1917, the Tigra dam catastrophic failure occurred due to seepage within the dam body. About 1,000 people lost their lives at the downstream of the dam. Another tragic seepage failure of the Teton dam located in the United States (US) eventuated on June 5, 1976. The death of 11 people and 13,000 cattle occurred and approximately 2 billion USD damages were estimated. Hence, seepage monitoring and studying are necessary to impede the expected failures.

The water flow is a critical and costliest issue during and after construction. It reduces the excavation speed and endangers the stability of a structure (Tseng *et al.*, 2001). Hence, seepage analysis is vital in the designing phase to ameliorate the hydraulic issues in civil engineering mostly in earthen dams. Various methods are adopted by researchers

for the monitoring and studying of seepage in dams such as numerical modelling, analytical methods and electrical resistivity tomography (Malkawi & Al-Sheriadeh, 2000; Soleimanbeigi & Jafarzadeh, 2005). Numerical simulations based on finite element method (FEM) were performed by several researchers for seepage determination through dams (Darbandi *et al.*, 2007; Lam *et al.*, 1987; Papagianakis & Fredlund, 1984; Potts *et al.*, 2001; Rushton & Redshaw, 1979; Uromeihy & Barzegari, 2007). SEEP/W (GEO-SLOPE International) software is a convenient tool to estimate the exit gradient, uplift thrust and seepage magnitude for a vast range of provisions (Khalili Shayan & Amiri-Tokaldany, 2015). Modern design practices are incorporated for controlling seepage in SEEP/W to analyze their effectiveness.

Different methods are used for controlling the seepage magnitude such as providing blanket at the upstream side, cut-off wall installation and cement grouting (MacGregor *et al.*, 2014; Shehata, 2006; Uromeihy & Barzegari, 2007). Khalili Shayan & Amiri-Tokaldany (2015) concluded that cut-off wall and U/S blanket are most beneficial in depleting the uplift thrust due to seepage and hydraulic gradient in the dam foundation.

In order to evaluate the seepage magnitude through Baz Ali small dam, this study focus on the finite element based computer package SEEP/W 2D for numerical simulation. Upstream clay blankets and cut-off walls of varying sizes were modelled to verify their effectiveness against seepage.

STUDY AREA INTRODUCTION

The Baz Ali small dam is located in Kurram Agency, Pakistan and 31 km away from Sadda town (Agency

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sub-headquarter). The project area is located at a latitude of 33°38′20′′ North and longitude as 70°14′90′′ East as shown in Figure 1. It is a developmental project in the water division which would provide instant consolation to the people of Kurram Agency by offering employment, recharging aquifer and enhancement of food yields. The proposed dam receives the perennial flow and flood from various tributaries. The height of Baz Ali dam is 24.30 m and having zoned embankment with shoulders containing river bed/spillways material and core of impervious clay. The spillway design discharge is grabbed as 503 m³/sec [17760 ft³/sec] for design flood period of 200 years.

The dam site mostly overlies on sedimentary limestone origin having colour from grey to pearly grey. The quaternary deposits and limestone on each side of Nainawar Khwar are un-fossiliferous and slightly fractured having a diverse configuration. The dam abutments will be constructed on rocks containing limestone which is moderately weathered. The removal of quaternary deposit is required from the structure area due to its poor engineering properties and low water tightness. Therefore, the foundation requires proper seepage remedial measures (Final Feasibility Report, 2010).

DARCY'S LAW

In 1856 Henry Darcy discovered an empirical solution to the flow through a soil mass. According to Darcy's theory, the fluid movement through the soil medium is directly proportional to the hydraulic conductivity and head loss per unit length of soil (Punmia & Jain, 2005). The seepage amount through porous materials can be expressed as:

$$Q = A \cdot v \qquad (1)$$

The velocity of flow is:

$$v = k \cdot i \qquad (2)$$

Putting the value of Equation (2) in Equation (1), the magnitude of seepage through the soil:

$$Q = k \cdot i \cdot A \qquad (3)$$

here,

Q	=	Discharge per unit time
k	=	Coefficient of permeability or hydraulic conductivity
i	=	Head loss per unit length or hydraulic gradient
A	=	Cross-sectional area through which fluid flow

LAPLACE SOLUTION FOR 2D/3D FLOW THROUGH SOIL

The flow of fluid in soil obeys the same fundamental equations for streamline flow. Laplace equation for both curvilinear and linear flow expressed the behaviour of flow within the soil pores. Muskat (1937) determined that the behaviour of fluid flow in steady-state within porous medium follows the fundamental laws as the problem of heat flow in steady-state, current flow in conductors and electrostatics (Cedergren, 1997).

Laplace assumed that the soil is incompressible, homogeneous and consolidation takes place. The flow through the soil medium adopts Darcy's law (Terzaghi *et al.*, 1996). The saturated soil element with a length of sides dx, dy and dz are shown in Figure 2. The water flow at the entrance and exist of soil element must be identical. v_x, v_y and v_z are the components of discharge velocity vector at the mid of soil unit in the x, y and z directions.

$$\frac{dv_x}{dx} \cdot i + \frac{dv_y}{dy} \cdot j + \frac{dv_z}{dz} \cdot k = 0 \qquad (4)$$

The velocity unit vectors i, j and k representing the direction of flow. Darcy's law ($v = k.i$) in terms of discharge velocities in the x, y and z coordinates are:

$$v_x = k_x \cdot \frac{dh}{dx}, \qquad v_y = k_y \cdot \frac{dh}{dy}, \qquad v_z = k_z \cdot \frac{dh}{dz}$$

Hence $k_x = k_y = k_z = k$ for isotropic soil and substituting these values in Equation (4).

$$d\frac{k(\frac{dh}{dx})}{dx} + d\frac{k(\frac{dh}{dy})}{dy} + d\frac{k(\frac{dh}{dz})}{dz} = 0 \qquad (5)$$

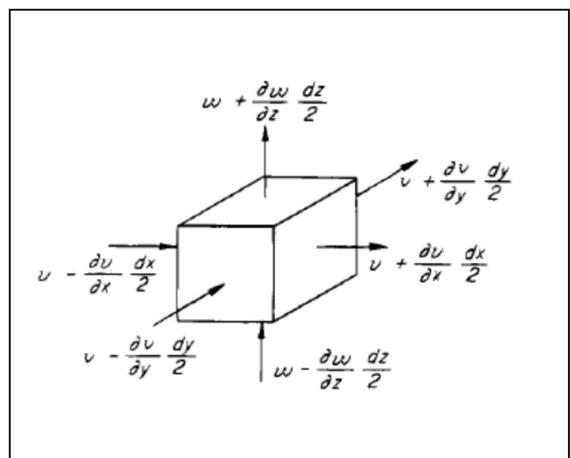**Figure 1:** Location map of the study area.

Figure 2: Discharge velocity elements at six faces of a soil element (from Terzaghi *et al.*, 1996).

If the permeability k value is constant

$$\frac{d^2h}{dx^2} + \frac{d^2h}{dy^2} + \frac{d^2h}{dz^2} = 0 \qquad (6)$$

Equation (6) is a general shape of the Laplace equation in three dimensions for water flow within the porous medium.

$$\frac{d^2h}{dx^2} + \frac{d^2h}{dz^2} = 0 \qquad (7)$$

The Equation (7) represents the water flow in two directions, which has been explained by two sets of the curved line intersecting each other at 90° and make square shapes called flow net. The horizontal line representing the flow path across the section is known as flow lines or streamlines. While the vertical lines are called equipotential line, joining the line of equal head or energy level (Cedergren, 1997; Sadrekarimi *et al.*, 2011).

NUMERICAL SIMULATIONS IN SEEP/W

Analytical methods for seepage determination are mostly used as a standard practice for a long period in developmental projects on rock/soil masses. Nowadays the use of quantitative procedures based on numerical simulation is an emerging standard of practice. SEEP/W, PLAXSIS, FLAC, FEEFLOW, UDEC, FLUENT and MODEFLOW are common computer generated softwares used for the numerical analysis. The finite element method (FEM) computer package SEEP/W is mostly used by geotechnical engineers for seepage determination through a foundation of dams/weirs. The seepage analysis in SEEP/W modelling utilizes the basic equation of Darcy's Law (Yoo *et al.*, 2016). It is used for the saturated and unsaturated state of groundwater flow and excess pore-water pressure (pwp) within porous mediums like soil and rock (Alam & Ahmad, 2015; Hsu & Chien, 2016). Goharnejad *et al.* (2010) modelled and analyzed the Farim Sahra dam of Iran with the application of SEEP/W. SEEP/W was also used for the analysis of two/three-dimensional models of Gotvand dam foundation and their models outputs were compared with each other (Sadrekarimi *et al.*, 2011).

SEEP/W was used for the numerical modelling of Baz Ali small dam by defining the problem in the software. Figure 3 demonstrates the dam body section with designated materials. In SEEP/W modelling with steady-state analysis, the material to each section was assigned in accordance with the field and laboratory tests result performed for the dam site (Final Feasibility Report, 2010). Table 1 describes the hydraulic conductivity values for modelling materials in SEEP/W.

RESULTS AND DISCUSSIONS

The comparison of numerical simulations and cost analysis are discussed for cut-off walls and upstream blankets with a filter. It is evident from the results that seepage is occurring through the dam foundation, so a proper remedial measure is required to eliminate the seepage through the dam body. Various techniques like a cut-off divider, cut-off trenches, cover grouting, upstream impervious blanket, pressure relief wells, chimney drains, horizontal drains
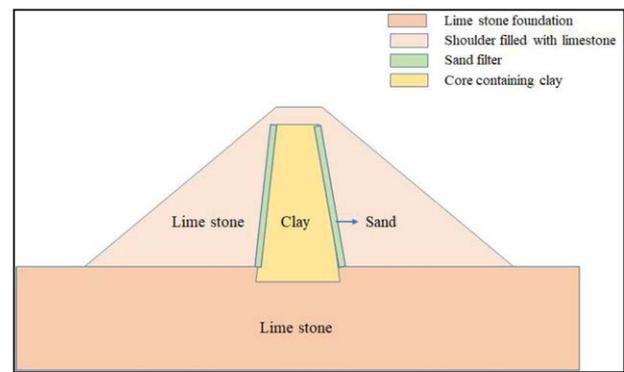

Figure 3: Typical section showing various materials in dam body of Baz Ali Small Dam.

Table 1: Laboratory permeability values for various dam materials.

S/NO	Materials	Permeability value[m.sec^{-1}]
1	Clay	7.14 x 10^{-7}
2	Shell/Shoulder materials	2.71 x 10^{-4}
3	Filter materials	1x10^{-4}

and weighting berm are adapted to impede the seepage of permeable unconsolidated materials (MacGregor *et al.*, 2014; Shehata, 2006).

Effect of filter on seepage quantity

Filters are acclimatized in dam body to prevent the transportation of fine soil particles. Filters can retain the phreatic line within the dam body and hence prevent the downstream slope from seepage failure (Chahar & Kalsi, 2004). The sand filter with a 1 m thickness in the shell is imparted as illustrated in Figure 4H. The SEEP/W results shown in Table 2 describe that seepage is reduced with a minor effect of 0.23% for the filter as compared with the base case but enhanced the overall structural stability. The sand filter ensures the reduction in uplift pressure generated at downstream and also eliminates the sand boiling and probable piping failure, so the filter is introduced in each control measures.

Effect of cut-off walls on seepage quantity

Small dams are mostly built on strata usually containing bedrock at a greater depth (Alam & Ahmad, 2015). When the foundation materials are pervious then seepage precaution becomes vital. Cut-off wall/trench is regarded as the best solution if the bedrock lies at a shallow depth (Novak *et al.*, 2007). Cut-off walls with varying depth and thickness were suggested as another alternative for seepage remediation. Cut-off walls of 5 m, 7.5 m and 10 m deep having 0.5 m and 1 m thickness was modelled in SEEP/W. The result presented in Table 2 shows that increasing the depth of cut-off wall results in seepage reduction. The SEEP/W results demonstrate that the seepage quantity diminished in contrast with the base trail by 1.05%, 10.15% and 19.75% for the cut-off wall of thickness 0.5 m and length of 5 m,
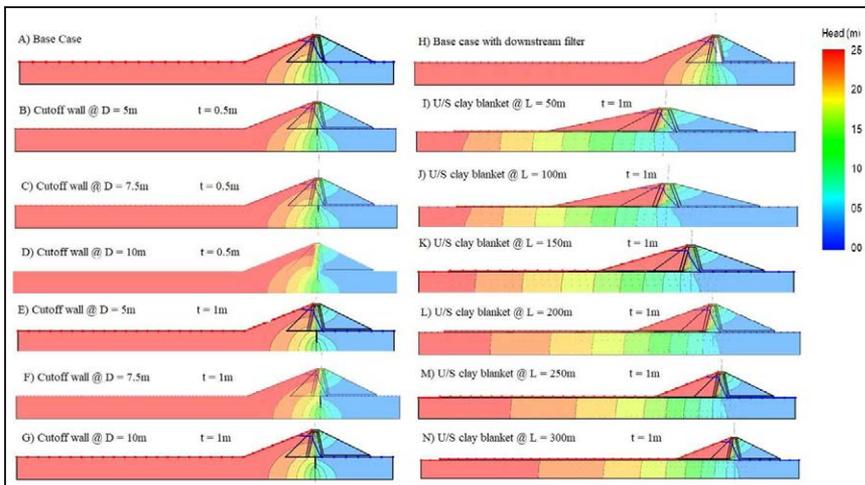
Figure 4: (A) Shows the SEEP/W model results for the base case without any control system. (B-G) Represent the model's results for cut-off walls. (H) Describe the model results for downstream filters. (I-N) Present the seepage contours for U/S clay blankets with various length.

Table 2: SEEP/W models results for different seepage remedial methods.

Trails	Dam Section	Thickness(t) [m]	D = Depth, L = Length [m]		Seepage quantity from SEEP/W Models [m³/sec]
1	Base Case	Without control measures			0.0025352
2	Down-Stream Filter	1			0.0025293
3	Cut-off wall	0.5	D	5	0.0025087
4				7.5	0.0022778
5				10	0.0020345
6		1		5	0.0024771
7				7.5	0.0022216
8				10	0.0019938
9	Upstream (U/S) impervious clay blanket	1	L	50	0.0011372
10				100	0.0010482
11				150	0.001023
12				200	0.0010142
13				250	0.0010115
14				300	0.0010106

7.5 m and 10 m respectively. The model outcomes of 1 m wide with the same cut-off wall lengths yield in seepage remediation of 2.29%, 12.37% and 21.36% correspondingly.

Effect of upstream clay blankets on seepage quantity

MacGregor *et al*. (2014) observed that the immense depth of low permeable tract makes cut-off wall strenuous to entirely penetrate and properly anchor with low permeability section. It is perceived that even cutoff wall is embedded 90% into the sub-stratum having no remarkable improvement in seepage remediation. However, horizontal U/S drainage blanket or pressure reduction systems should consistently impart for a permeable dam foundation (Lane & Wohlt, 1961).

U/S impervious clay blankets were adopted for diminishing hydraulic gradient and seepage amount at the downstream section. The U/S clay blanket of 1 m thickness were modelled with the corresponding lengths of

50 m, 100 m, 150 m, 200 m, 250 m and 300 m as shown in Figure 4I-N. The seepage volume for a 50 m long U/S clay blanket gives 0.0011372 cumecs which exhibit a reduction of 55.14% as compared to the dam section without control measure. Similarly, U/S clay impervious blankets of length 100 m, 150 m, 200 m, 250 m and 300 m having 1 m thickness reduce the seepage magnitude by 58.65%, 59.65%, 60%, 60.10% and 60.14% respectively as compared with the base model which is represented in Figure 5. However, the analysis validates that increasing the blanket length after a certain limit has no significance on seepage reduction.

Cost analysis of control systems

Cost analysis is a growing practice adopted to determine the economic viability of a project. Hence, the cost of all feasible intervention remedial techniques is compared to evaluate the appropriate method for seepage reduction.
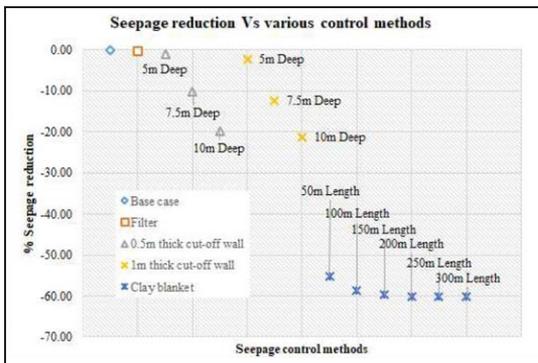
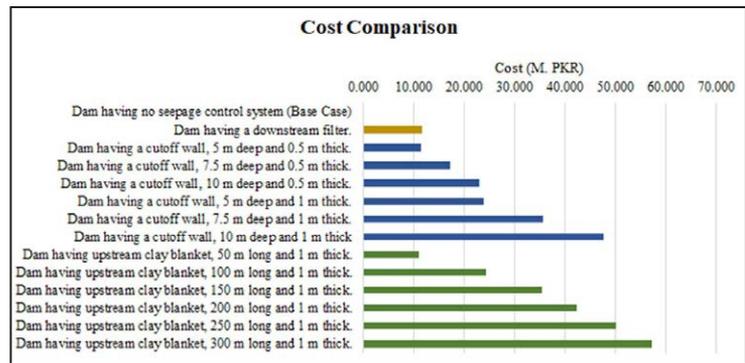**Figure 5:** Seepage reduction for various trails as compared with the base case model.

Figure 6: Cost comparison for the various trail in Pakistani Rupees (PKR).

Figure 6 represents the cost analysis comparison calculated in millions for each trail on the basis of a composite schedule of rates (CSR) Khyber Pakhtunkhwa (CSR, 2012). The following formula was adopted for the calculation of cost.

Cost = Quantity × CSR rate × Area factor

The costs were calculated in Pakistani rupees (PKR) and the area factor (A.F) for Kurram agency is 0.05. The cost for the dam having a filter on the downstream side is 11.69 million. The expenses for cut-off walls having a thickness of 0.5 m and length of 5 m, 7.5 m and 10 m are 11.46, 17.19, and 22.92 million, so for the same length of cut-off walls with 1 m thickness, the estimated cost become 23.82, 35.73 and 47.64 million PKR respectively. The corresponding cost for upstream clay blanket with 1 m thickness and length of 50 m, 100 m, 150 m, 200 m, 250 m and 300 m are 10.90, 24.21, 35.30, 42.31, 50.02 and 57.16 million PKR. The cost analysis reveals that the cut-off wall is an expensive technique than upstream impervious clay blanket. On the other hand, the clay blanket is a more efficient and cost-effective method for controlling the seepage through dam foundation.

CONCLUSIONS

The Baz Ali small dam was modelled in SEEP/W software for determination of seepage amount. The models without seepage control arrangement validate that seepage has been occurring within the dam foundation. In this study, the applicability of D/S sand filter with cut-off wall and U/S impervious clay blanket are tailored on the basis of seepage reduction efficiency and economic analysis. The numerical model result illustrates that D/S sand filter has a minor effect on seepage remediation but increase the stability against uplift thrust. The provision of cut-off walls has no prominent reduction in seepage. The U/S clay blanket offered an extensive depletion of seepage through the dam foundation. The cost analysis for all seepage remedial measures shows that the clay blankets up to 100 m length are the most efficient and economical. The SEEP/W analysis also validates that increasing the length of U/S impervious blanket from a certain value such as 100 m has insignificant upshot on seepage controlling and also make the technique expensive. In order to enhance the Baz Ali small dam stability, U/S clay blanket of 100 m length is proposed for seepage remediation.

REFERENCES

Alam, I. & Ahmad, I., 2015. Sensitivity study of different parameters affecting the design of the clay blanket in small earthen dams. Journal of Himalayan Earth Sciences, 48 (2), 139.

Cedergren, H. R., 1997. Seepage, drainage, and flow nets. John Wiley & Sons, USA. 465 p.

Chahar, B. & Kalsi, A., 2004. Design of horizontal filter length in homogeneous earth dams. ISH Journal of Hydraulic Engineering, 10 (1), 8-18.

Chen, Y., Wang, Y. & Zhang, Q. Y., 2014. Coupled seepage-elastoplastic-damage analysis of saturated porous media and its application to water conveyance tunnel. Tunnelling and Underground Space Technology, 44, 80-87.

CSR, 2012. Composite Schedule of Rates 2012. Khyber Pakhtunkhwa.

Darbandi, M., Torabi, S., Saadat, M., Daghighi, Y. & Jarrahbashi, D., 2007. A moving-mesh finite-volume method to solve free-surface seepage problem in arbitrary geometries. International Journal for Numerical and Analytical Methods in Geomechanics, 31 (14), 1609-1629.

Final Feasibility Report, 2010. Geotechnical Investigations and Laboratory Testing, Volume-III, 2010. Small Dams Section, FATA Development Authority Peshawar.

Ghobadi, M., Khanlari, G. & Djalaly, H., 2005. Seepage problems in the right abutment of the Shahid Abbaspour dam, southern Iran. Engineering Geology, 82 (2), 119-126.

Goharnejad, H., Noury, M., Shamsaie, A. & Goharnejad, A., 2010. The effect of clay blanket thickness to prevent seepage in dam reservoir. Research Journal of Environmental Sciences, 4 (6), 558-565.

Hsu, C.-F. & Chien, L.-K., 2016. Slope stability analysis of transient seepage under extreme climates: a case study of typhoon nari in 2001. Journal of Marine Science and Technology, 24 (3), 399-412.

Khalili Shayan, H. & Amiri-Tokaldany, E., 2015. Effects of blanket, drains, and cutoff wall on reducing uplift pressure, seepage, and exit gradient under hydraulic structures. International

Journal of Civil Engineering, 13 (4), 486-500.

Lam, L., Fredlund, D. & Barbour, S., 1987. Transient seepage model for saturated–unsaturated soil systems: a geotechnical engineering approach. Canadian Geotechnical Journal, 24 (4), 565-580.

Lane, K. & Wohlt, P., 1961. Performance of sheet piling and blankets for sealing Missouri River reservoirs. Proceedings of the 1961 Proc., 7th Congress on Large Dams, Rome, 255-279.

MacGregor, P., Fell, R., Stapledon, D., Bell, G. & Foster, M., 2014. Geotechnical engineering of dams: CRC press.

Malkawi, A. I. H. & Al-Sheriadeh, M., 2000. Evaluation and rehabilitation of dam seepage problems. A case study: Kafrein dam. Engineering Geology, 56 (3-4), 335-345.

Muskat, M., 1937. The flow of fluids through porous media. Journal of Applied Physics, 8(4), 274-282.

Novak, P. M., A.I.B. Moffat, Nalluri, C. & Narayanan, R., 2007. Hydraulic Structures (4th ed.). CRC Press. 736 p.

Papagianakis, A. & Fredlund, D., 1984. A steady state model for flow in saturated–unsaturated soils. Canadian Geotechnical Journal, 21 (3), 419-430.

Potts, D. M., Zdravkovic, L. & Zdravković, L., 2001. Finite element analysis in geotechnical engineering: application. Thomas Telford, UK. 440 p.

Punmia, B. & Jain, A. K., 2005. Soil mechanics and foundations. Laxmi Publications, New Delhi, India.

Qureshi, M. S. & Aziz, A., 2011. Fundamentals of soil mechanics (2nd Edition Ed.) A-One Publishers, Lahore, Pakistan. 465 p.

Rushton, K. R. & Redshaw, S. C., 1979. Seepage and groundwater flow: Numerical analysis by analog and digital methods. Wiley, New York. 339 p.

Sadrekarimi, J., Kiyani, M., Fakhri, B., Vahdatirad, M. J. & Barari, A., 2011. Seepage analysis of Upper Gotvand Dam concerning gypsum karstification (2D and 3D approaches). Frontiers of Architecture and Civil Engineering in China, 5 (1), 71-78.

Shehata, A., 2006. Design of downstream blanket for overflow spillway founded on complex formation. J. Appl. Sci. Res., 2 (12), 1217-1227.

Soleimanbeigi, A. & Jafarzadeh, F., 2005. 3D steady state seepage analysis of embankment Dams. Electronic Journal of Geotechnical Engineering (EJGE), 10.

Terzaghi, K., Peck, R. B. & Mesri, G., 1996. Soil mechanics in engineering practice. John Wiley & Sons, New York. 549 p.

Tseng, D.-J., Tsai, B.-R. & Chang, L.-C., 2001. A case study on ground treatment for a rock tunnel with high groundwater ingression in Taiwan. Tunnelling and Underground Space Technology, 16 (3), 175-183.

Uromeihy, A. & Barzegari, G., 2007. Evaluation and treatment of seepage problems at Chapar-Abad Dam, Iran. Engineering Geology, 91 (2-4), 219-228.

Venkatramaiah, C., 2006. Geotechnical engineering: New Age International, New Delhi. 926 p.

Yoo, C., Ku, J. M., Jun, C. & Zhu, J. H., 2016. Simulation of infiltration facilities using the SEEP/W model and quantification of flood runoff reduction effect by the decrease in CN. Water Science and Technology, 74(1), 118-129. https://doi.org/10.2166/wst.2016.189.