Design of optimum remedial measures and its effect on seepage and stability aspects of an earth dam

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ABSTRACT:

Earth dams, which constitute one of the most complex structures built by mankind, are designed to withstand all possible destabilizing forces with certain factor of safety (FoS). However, the possibility of failure cannot be denied; one of the main reasons being excessive seepage. Every dam has a unique solution for mitigating seepage owing to its site specific nature. Present paper describes the potential of numerical modeling technique in quantification of seepage parameters and designing optimum remedial measures by taking into account safety aspects of the dam. Analysis using software PLAXIS-2D for a multi-zoned earth dam indicates heavy seepage of 4.451 m^3/day/m, majorly through foundation. Effect of cut-off-wall, upstream blanket and upstream slope lining is studied, individually as well as in combination. Variation of seepage quantity with cut-off-wall at four locations A, B, C and D and with different depths (10 m, 20 m and 30 m) indicates that wall at positions B and C is effective as compared to positions A and D. Total seepage reduces by 37.04% with cut-off-wall of depth 30 m at position C and by 25.66% with cut-off-wall of depth 30 m at position B. Up to depth of 22.5 m, position B is effective than C. However, for cut-off-wall more than 22.5 m depth; position C is effective than B. No effect of upstream horizontal blanket is seen in reducing seepage; however combination of upstream horizontal blanket with slope lining is effective. The discharge reduces consistently from 4.073 m^3/day/m to 2.765 m^3/day/m with increase in length of clay blanket from 10 m to 100 m with slope lining. This accounts to 39.11% reduction in discharge as compared to dam cross-section with no remedial measure. Determination of FoS by strength reduction technique indicates no significant change in value for steady seepage condition with and without remedial measures. However, the FoS for drawdown reduces significantly with cut-off-wall as remedial measure. In the present study, complexity of the problem due to multiple zoning is tackled with numerical modeling. Analysis helps in selecting optimum remedial measures considering seepage and stability aspects.

1 INTRODUCTION

Earth dams are used to impound water for various purposes such as irrigation, power generation, domestic and industrial water supply, etc. Every earth dam has water percolating through or under the dam as the soil / rock material used for its construction and that existing in the foundation, is pervious. This passage of water, known as seepage, must be controlled in both velocity and quantity. If uncontrolled, it can progressively erode soil, resulting in risk to structural safety of the dam due to damages viz. piping, slope failure, settlement, etc. There are reported incidences of catastrophic dam failures due to excessive seepage. Uncontrolled seepage also leads to loss of precious water and thus may impede the very purpose of constructing a dam.

Various remedial methods viz. (a) cut-off-trench (positive or partial), (b) concrete cut-off walls, (c) grout curtains, (d) slurry trench cut-offs (earth backfilled), (e) sheet piles, (f) upstream impervious blankets, (g) vertical drains, (h) upstream slope lining, etc are adopted to mitigate seepage through earth dams. Provisions for seepage control have two functions viz. (i) reduction of water loss to an amount compatible with purpose of the project and (ii) elimination of possibility of dam failure due to structural damages. Certain remedial measures are required to be adopted in design stage of the dam owing to unfavourable geological conditions or non-availability of suitable soil material for construction of the dam. Certain measures are required to be adopted in operational stage owing to structural damages or excessive water loss due to seepage. In certain cases, due to nonperformance of remedial measures adopted in design stage, additional measures are required in operational stages. At times, to achieve multiple line of defense; more than one type of seepage control measures are required. Remedial measures are site specific in nature and those best suited for a particular project depend upon many factors, but most importantly on (i) ensuring safety of the dam and (ii) economic considerations.

The present paper highlights prowess of numerical modellling technique in optimizing seepage remedial measures considering safety aspects of the dam. Various trials of different remedial measures viz. upstream blanket, cut-off-wall and upstream slope lining are studied individually and in combination using 2D numerical modeling software PLAXIS for a multi zoned earth dam section with high foundation seepage. Seepage discharge and dam stability in terms of Factor of safety (FoS) are compared for all the cases. The studies help in selecting optimum remedial measures considering seepage and stability aspects.

2 FORMULATIONS TO SEEPAGE PROBLEMS

Flow of seepage water through body of earth dam and foundation is governed by Laplace's equation for two dimensional flow (Equation 1) and Darcy's relation (Equation 2) for flow through porous media.

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = 0 \tag{1}$$

$$q = k \frac{\partial h}{\partial s} \tag{2}$$

where k_x, k_y = soil permeability; $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}$ = hydraulic gradient; and q = seepage discharge

Solutions to steady-state, laminar flow seepage problems are determined by solving Laplace's equation. Several methods have been developed to solve exactly or approximately Laplace's equation for seepage. In earlier days sand models, electrical analogy methods, viscous flow methods, etc were used to determine flow conditions. Analytical and graphical methods were also developed. With the advent of computers, numerical methods have gained popularity due to ease of adapting to complex flow situations. The two primary methods of numerical solution are finite difference and finite element. Both can be used in one, two or three dimensional modeling. Several computer programs for finite difference and finite element methods are available commercially. PLAXIS-2D is a finite element programme used for two dimensional analysis of seepage, deformation and stability in geotechnical engineering. In finite element method the flow region is divided into smaller units, called finite elements. Material properties such as density, shear strength, elasticity parameters and permeability of the regions are assigned. Boundary conditions that cause flow of water, i.e. maximum water level on upstream side and tail water on downstream side are specified to the numerical model. The model is executed to get solution in the form of equipotential lines and flow lines along with other parameters of interest, viz. pore pressure, hydraulic gradient, water head, seepage discharge, etc at different locations. By creating a slender impervious zone with very low permeability to the order of $1E^{-9}$ m/sec, remedial measures such as cut-off-wall, impervious blanket, diaphragm wall, etc can be simulated in the model.

3 2D NUMERICAL MODEL STUDY FOR EARTH DAM

Present study is conducted for an existing multi-zoned earth dam constructed for lift irrigation scheme. Maximum height of the dam is 57.5 m and length is 3.375 km. Dam cross-section considered for analysis is shown in Fig.1. Due to non-availability of casing soils in submergence area, original two-zoned dam cross-section is modified to multi-zoned, with fives zones constructed of different types of soil. The cross-section comprises of impervious hearting (Zone 2) and pervious / semi-pervious casing (Zone 1, Zone 3, Zone 4 and Zone 5). Foundation strata of the dam consist of top soil (Well graded gravel - GW) of thickness 2 m underlain by highly to slightly weathered granite rock strata. A central partial cut-off-trench (CoT) of base-width 10.0 m and depth 7.645 m below hearting is provided to restrict seepage through foundation. Soil parameters in dam body and foundation adopted for study are listed in Tables 1 and 2 respectively.

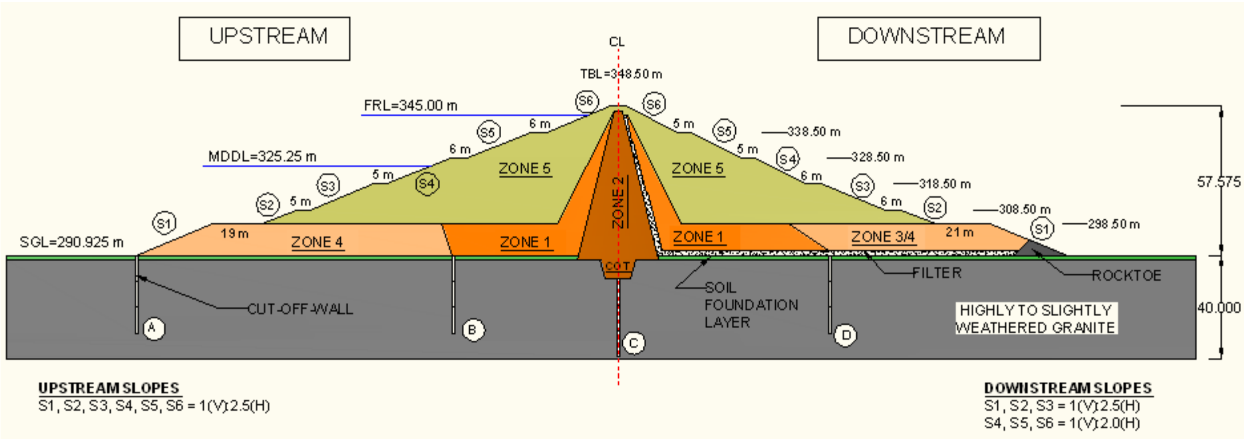

Figure 1. Cross-section of Multi-zoned dam

Table 1. Parameters of soil in dam body

Sr.No.	Parameter	Zone 1	Zone 2	Zone 3/4	Zone 5	Filter	Rocktoe
1	Bulk density (kN/m^3)	19.93	19.01	20.66	22.15	18.00	20.00
2	Saturated density (kN/m^3)	20.91	19.43	21.56	22.67	18.00	20.00
3	Cohesion (kN/m^2)	25	40	3	5	0	0
4	Friction Angle (deg.)	22^0	7^0	39^0	45^0	30^0	40^0
5	Young's Modulus of elasticity (kPa)	$4.28X10^4$	$2X10^4$	$7X10^4$	$7X10^4$	$5X10^4$	$2X10^5$
6	Poisson's ratio	0.35	0.45	0.30	0.30	0.30	0.28
7	Permeability (m/sec)	$18.62X10^{-8}$	$7.34X10^{-9}$	$5.25X10^{-4}$	$5.25X10^{-4}$	$4.63X10^{-4}$	$1X10^{-3}$

Table 2. Parameters of soil / rock in foundation

Sr.No.	Parameter	Soil	Granite in foundation
1	Bulk density (kN/m^3)	20.95	23.00
2	Saturated density (kN/m^3)	24.29	24.00
3	Cohesion (kN/m^2)	1	23
4	Friction Angle (deg.)	32^0	35^0
5	Young's Modulus of elasticity (kPa)	$7X10^4$	$8X10^4$
6	Poisson's ratio	0.30	0.28
7	Permeability	$4.5X10^{-5}$ (m/sec)	22.46 Lugeon*

** 1 Lugeon = $1X10^{-7}$ m/sec*

4 SEEPAGE AND STABILITY ANALYSIS

The first step in design of seepage control measures is to estimate the quantity of water that may escape if no attempt is made to intercept seepage. In the present case the total quantity of seepage discharge with no remedial measures, except partial CoT in existing design, works out to be 4.541 m^3/day/m. From results of analysis it is seen that about 98.5% of total seepage is occurring thorough foundation. Considering that the dam is already existing; to mitigate quantity of seepage, two types of remedial measures can be adopted viz. (i) those intercepting foundation layers viz cut-off-wall, grout curtain, etc and (ii) those lengthening the seepage path viz. upstream horizontal blanket. Depending on the seepage quantity, above measures can be adopted with or without upstream slope lining to reduce quantity of seepage through dam body. Numerical modeling is used to study the efficacy of each of the above measures. For optimization, different trials are analysed by varying the position and depth of cut-off wall, length of horizontal blanket in combination and without upstream slope lining. The cases analysed are listed below :

i. **Cut-off-wall** – At four different positions A, B, C and D with varying depths 10 m, 20 m and 30 m; Case Nos. 1 to 12 (Total 12 cases)

ii. **Up-stream horizontal blanket** – Varying length 20 m, 40 m, 60 m, 80 m and 100 m; Case Nos. 13 to 17 (Total 5 cases)

iii. **Up-stream horizontal blanket with slope lining** – Varying length of blanket 10 m, 20 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m, 100 m; Case Nos. 18 to 27 (Total 10 cases)

Thus in all 27 cases with different remedial measures are analysed. The cases are run in fully coupled mode of analysis in software PLAXIS-2D followed by safety calculation for determination of Factor of Safety (FoS) by strength reduction method. A fully coupled flow deformation analysis is conducted to analyse simultaneous development of deformations and pore pressures as a result of time dependent changes in hydraulic boundary conditions. In strength reduction method of safety calculation, the shear strength parameters viz. cohesion (c) and angle of internal friction (ϕ) are successively reduced until failure occurs. Total multiplier $\sum M_{sf}$ is used to define the value of soil strength parameters at given stage of analysis. The FoS (SF) is given by :

$$SF = \frac{available\ strength}{strength\ at\ failure} = \text{value of } \Sigma Msf \text{ at failure}$$

Seepage parameter viz. discharge quantity and safety parameter viz. FoS in terms of $\sum M_{sf}$ is determined and compared for all cases of study. Results are presented in para 5.

5 RESULTS OF SEEPAGE ANALYSIS

Results of seepage analysis for various cases of study are described below.

i. **Cut-off-wall (Case Nos. 1 to 12) :** Variation in seepage discharge with depth and position of cut-off-wall is shown in Figure 2. It is seen that due to reduction in seepage discharge at positions B and C; cut-off-wall at these positions is effective as compared to positions A and D. Total seepage reduces by 37.04% with cut-off-wall of depth 30 m at position C and by 25.66% with cut-off-wall of depth 30 m at position B. Optimum position of cut-off-wall (B or C) depends on the depth of wall to be constructed at site. Depth can be ascertained from permissible seepage discharge of the project. Up to depth of 22.5 m, position B is effective than C. However, for cut-off-wall more than 22.5 m depth; position C is effective than position B.

ii. **Upstream horizontal blanket (Case Nos. 13 to 17) –** Five cases with increasing length of upstream horizontal blanket (20 m, 40 m, 60 m, 80 m and 100 m) are analysed. Variation in seepage discharge with length of blanket is shown in Figure 3. It is seen that the horizontal blanket has no effect in reducing total seepage discharge. In general, upstream horizontal blanket extending up to hearting zone in dam body proves to be effective in arresting seepage through pervious overburden soil in foundation. However, in the present case, since the dam is already constructed, upstream blanket from hearting zone cannot be provided. Also, the overburden soil thickness is only 2 m and as compared to overburden soil; zones 4 and 5 in casing of dam body are more pervious. Hence no effect of upstream horizontal blanket is seen in reducing seepage. As such, upstream horizontal blanket in combination with upstream slope lining is studied.

iii. **Upstream horizontal blanket in combination with slope lining (Case Nos. 18 to 27) –** To mitigate seepage through pervious zones 4 and 5 in upstream casing of the dam and through foundation as well, remedial measure in the form of upstream horizontal blanket in combination with slope lining is analysed. Variation of seepage discharge with length of upstream horizontal blanket is shown in Figure 4. It is seen that the combination of upstream horizontal blanket with slope lining proves to be effective in mitigating seepage. The discharge reduces consistently from 4.073 m^3/day/m to 2.765 m^3/day/m with increase in length of clay blanket from 10 m to 100 m. This accounts to 39.11% reduction in discharge as compared to dam cross-section with no remedial measure.

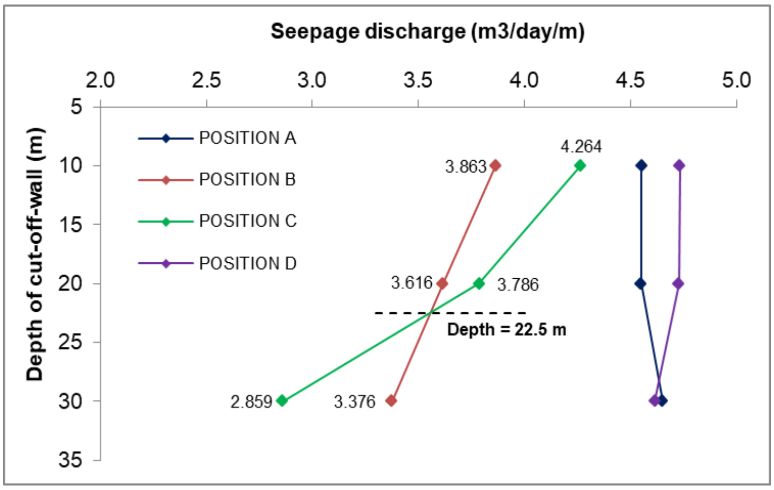

Figure 2. Variation of seepage discharge with depth and position of cut-off-wall (cases 1 to 12)

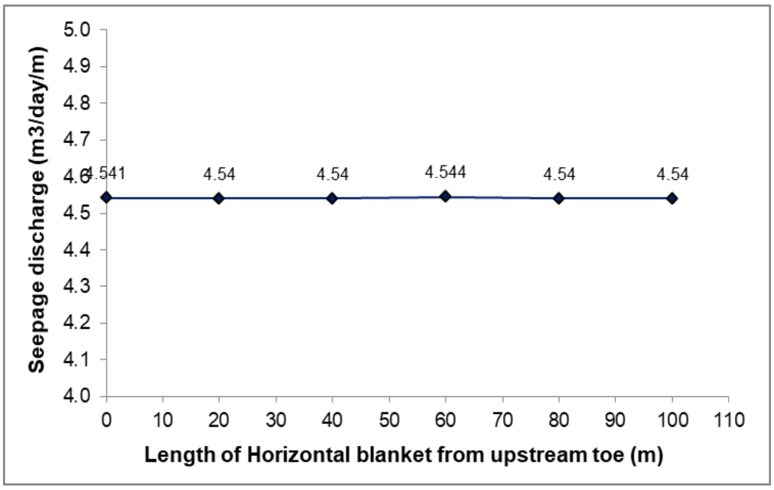

Figure 3. Variation of seepage discharge with length of upstream horizontal blanket (cases 13 to 17)

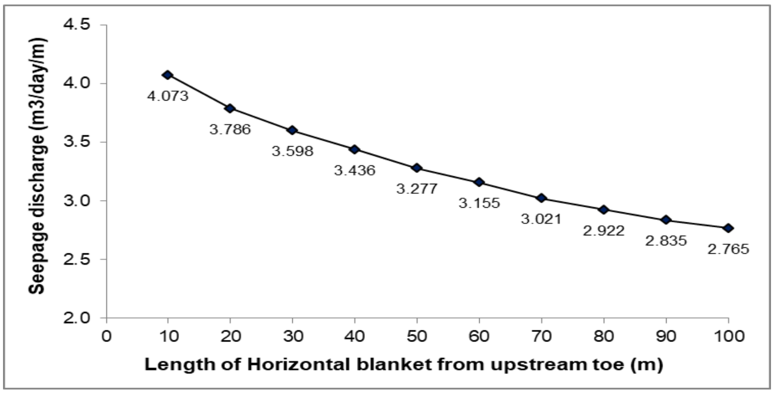

Figure 4 : Variation of seepage discharge with length of upstream horizontal blanket with slope lining (cases 18 to 27)

6 RESULTS OF SLOPE STABILITY ANALYSIS

The values of FoS by strength reduction technique for steady seepage condition for all cases of study are shown in Figures 5, 6 and 7. No significant variation in FoS is seen for all cases of cut-off-wall (cases 1 to 12) and upstream horizontal blanket (cases 13 to 17). However, gradual increase in FoS from 1.69 to 1.76 is seen with increase in length of upstream blanket with slope lining (cases 18 to 27). Steady seepage FoS for dam cross-section with no remedial measures works out to be 1.637. In comparison to this value, FoS for cases with remedial measures do not vary significantly.

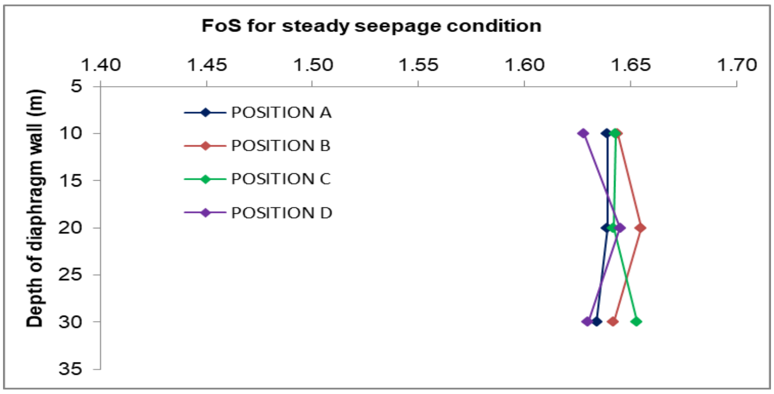

Figure 5 : Variation of FoS (steady seepage) with depth and position of cut-off-wall (cases 1 to 12)

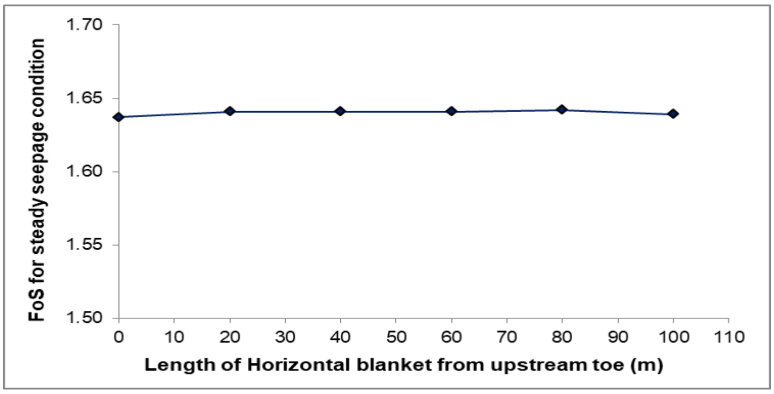

Figure 6 : Variation of FoS (steady seepage) with length of upstream horizontal blanket (cases 13 to 17)

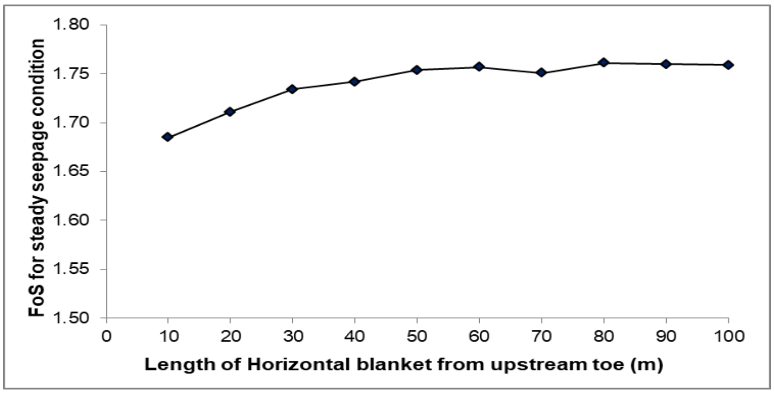

Figure 7 : Variation of FoS (steady seepage) with length of upstream horizontal blanket with slope lining (cases 18 to 27)

Safety of upstream slope is critical for sudden drawdown condition. Drawdown FoS for dam cross-section with no remedial measure works out to be 1.775. Variation in FoS for all cases of cut-off-wall (cases 1 to 12) is shown in Figure 8. A significant reduction as compared to dam cross-section with no remedial measure (1.775) is seen in FoS for cut-off-wall at all positions and depths. Also, as the position of cut-off-wall shifts towards downstream side from A to B, C or D; the value of FoS decreases.

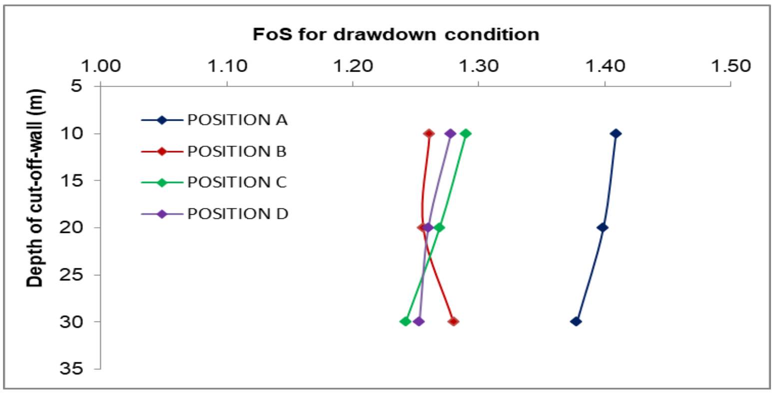

Figure 8 : Variation of FoS (drawdown) with depth and position of cut-off-wall (cases 1 to 12)

7 CONCLUSION

Analysis by numerical modeling plays an important role in deciding appropriate seepage remedial measures for an earth dam. Modelling helps in computing acceptable level of seepage quantity, hydraulic head, pore pressures, etc for various combinations of remedial measures and their effect on safety aspects of the dam. In the present study, remedial measures viz. cut-off-wall, upstream horizontal blanket and blanket in combination with lining are studied for an existing multi zoned earth dam. From the results of seepage analysis following conclusions are drawn :

(i) Cut-off-wall at positions B and C is effective as compared to positions A and D. Total seepage reduces by 37.04% with cut-off-wall of depth 30 m at position C and by 25.66% with cut-off-wall of depth 30 m at position B. Up to depth of 22.5 m, position B is effective than C. However, for cut-off-wall more than 22.5 m depth; position C is effective than position B.

(ii) No effect of upstream horizontal blanket is seen in reducing seepage.

(iii) Combination of upstream horizontal blanket with slope lining is effective in mitigating seepage. The discharge reduces consistently from 4.073 m^3/day/m to 2.765 m^3/day/m with increase in length of clay blanket from 10 m to 100 m. This accounts to 39.11% reduction in discharge as compared to dam cross-section with no remedial measure.

Safety consideration should be given due importance in determination of optimum seepage remedial measures. In the present case, no significant change in FoS for steady seepage condition with and without remedial measures is seen. However, the FoS for drawdown reduces significantly with cut-off-wall as remedial measure.

8 REFERENCES

Soleymani, S. and Akhtarpur, A. 2011. *"Seepage Analysis for Shurijeh Reservoir Dam Using Finite Element Method"*, Geo-Frontiers 2011, 3227-3234.

Behnam Mansuri, Farzin Salmasi 2011. *"Effect of Horizontal Drain Length and Cutoff Wall on Seepage and Uplift Pressure in Heterogeneous Earth Dam with Numerical Simulation"* Journal of Civil Engineering and Urbanism, Volume 3, Issue 3: 114-121 2013

Pouya Zahedi, Hamed Farshbaf Aghajani *"The Effect of Clay Core Specifications on the Seepage Behavior of an Earthfill Dam"* 5th International Symposium on Dam Safety, 27-31st Oct, 2018.

Armin Farzampour, Farzin Salmasi and Behnam Mansuri *"Optimum Size for Clay Core of Alavian Earth Dam by Numerical Simulation"* Iranica Journal of Energy & Environment 5 (3): 240-246, 2014

Harry R. Cedergrene "*Seepage, drainage and flow nets*" 1989, A Wiley Interscience Publications ISBN 0-471-61178-6

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