Optimization of Remedial Measures for Mitigation of Foundation Seepage in Earth Dam – A Case Study

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Abstract. Analysis by numerical modeling software PLAXIS 2D is carried out for the earth dam of Kurha-Vadhodha Islampur sinchan yojana, Maharashtra to optimize seepage remedial measures. Depending on the dam cross-sections and foundation stratification, four cases (A, B, C and D) are analyzed. Results of analyses indicate that for design dam cross-sections, major seepage is occurring through dam foundation with total discharge quantities of 0.7102, 0.7738, 0.2699 and 0.7169 m^3/day/m respectively. As these values are more than the permissible limit, seepage mitigation measures are required to be adopted at site. To determine the most effective remedial measure, analyses are conducted with: (i) rock grouting, (ii) cutoff wall below CoT and (iii) upstream horizontal blanket in combination with a 6 m deep cutoff wall. Trials are conducted with different depths of cutoff wall and different lengths of horizontal blanket for optimization. For each trial, efficacy is determined by comparing discharge quantity with the permissible limits. Results indicate that seepage discharge quantities with cutoff wall of depth 35 m, 30 m, 5 m and 15 m for cases A, B, C and D are 0.1936, 0.1892, 0.1602 and 0.1751 m^3/day/m respectively; which are less than the upper permissible limit. Hence cutoff wall of above depths is recommended as the most effective seepage remedial measure for the earth dam of Kurha-Vadodha Islampur sinchan yojana.

Keywords: Earth Dam, Foundation Seepage, Rock Grouting, Cutoff wall, Upstream Blanket.

1 Introduction

Earth or embankment dam is a hydraulic structure constructed to create a reservoir on its upstream side for water storage. Stored water is released in a controlled manner for various purposes viz. irrigation, power generation, domestic or industrial water supply, flood control, etc. An earth dam is constructed by placement and compaction of different types of soil/ rockfill material where friction and interaction between particles bind them into a stable mass rather than by use of any cementing material. Construction of earth dam is very popular and widely used in India because they can be built on any type of foundation and their construction is comparatively economical. However, earth dams also have many limitations in terms of complexity in their design, construction, maintenance and susceptibility to seepage. Seepage is an inevitable phenomenon in earth dams, occurring due to hydraulic head difference on upstream and downstream sides and due to the inherent porous nature of soil material. Uncontrolled seepage flow through the dam body and foundation leads to internal erosion and piping, causing failure of earth dams in almost 30–50% of cases [1]. Also, as the primary purpose of most earth dams is to store water during flood season and use it for entire year; excess water loss through seepage is undesirable. While seepage through dam body can be controlled by selecting adequate soil material such as impervious clay in the hearting zone and compacting it to optimum density [2-4]; seepage through foundation, is a major concern at times, especially for a dam which is sited over weak/ pervious foundation. Implementation of optimum foundation seepage mitigation measures becomes of utmost importance in such cases. While different remedial measures viz. foundation grouting, cutoff wall below COT, upstream cutoff wall, upstream impervious horizontal blanket, etc. [5] can be adopted to arrest foundation seepage; it is important to select and optimize the most effective site-specific remedial measure in terms of seepage discharge reduction. At times, combination of more than one measure is required for obtaining desired results. Seepage analyses using numerical modeling are a great tool to determine optimum site-specific solutions to seepage problems. In this paper, a case study of selecting the optimum foundation seepage mitigation measure for the earth dam of Kurha-Vadhodha Islampur sinchan yojana, Maharashtra is presented. The best suitable and optimized seepage remedial measure is recommended for the dam based on the results of analyses.

2 Details of the Case Study

Kurha - Vadhodha Islampur sinchan yojana is proposed to irrigate about 25,898 hectares of land in Jalgaon and Buldhana districts of Maharashtra. The project envisages lifting about 100.09 million cubic meter of water (9.654 m^3/sec for 120 days) in three stages with a total lift of 115 m from Purna river during monsoon season and storing it in Islampur earth dam (full reservoir level of the dam is RL 325.5 m). Irrigation is proposed through the reservoir by means of two sluices with sill level at RL 300.0 m. The dam is sited across naturally available local nallas and is aligned in ‘U’ shape in plan such that its left limb extends between Ch. -15.0 m to Ch. 3165 m, central portion between Ch. 3165 m to Ch. 4805 m, right limb between 4805 m to Ch. 6830 m and waste weir between Ch. 6830 m to 6910 m. Total length of the dam excluding waste weir is 6845 m.

Seepage studies are conducted for dam cross-sections in two stretches viz. Stretch 1: from Ch. 990 m to 1290 m and Stretch 2: from Ch. 1650 m to 1920 m. Cross-section along entire length of the dam is two-zoned with central hearting constructed of impervious soil and outer casing constructed of pervious/ semi-pervious soil and rock matrix.

2.1 Foundation Strata

Islampur dam is located on an undulating terrain. Detailed geological investigation at site is conducted by 47 exploratory boreholes along total length of the dam, out of which 4 boreholes viz. BH-9 (Ch. 1095 m, depth 54.0 m), BH-13 (Ch.1650 m, depth 49.0 m), BH-14 (Ch. 1800 m, depth 40.0 m) and BH-15 (Ch. 1875 m, depth 38.5 m) are referred for finalizing foundation strata beneath dam cross-sections analyzed in the present study. Boreholes indicate that foundation strata in Stretch 1 comprises of overburden soil, underlain by 'Maan' type soil followed by alternate layers of compact and amygdaloidal basalt. 'Maan' is local nomenclature for clayey type of soil existing in vicinity of the project. The soil is white in colour and highly plastic. It exhibits shrinkage and swelling characteristics and has high water retaining property. The soil can be classified as CI or CH as per BIS. In Stretch 2, overburden soil is underlain by alternate layers of compact and amygdaloidal basalt. Black jointed compact basalt occurs at different levels in foundation. Fresh compact basalt with high recovery percentage occurs at deeper depths while weathered compact basalt with poor recovery occurs immediately below the foundation. Purple weathered amygdaloidal basalt occurs in foundation with varying thickness. As per the geotechnical investigation report, fresh rock is rarely encountered at shallow depths. Presence of weathered compact andamygdaloidal basalt makes the foundation prone to seepage.

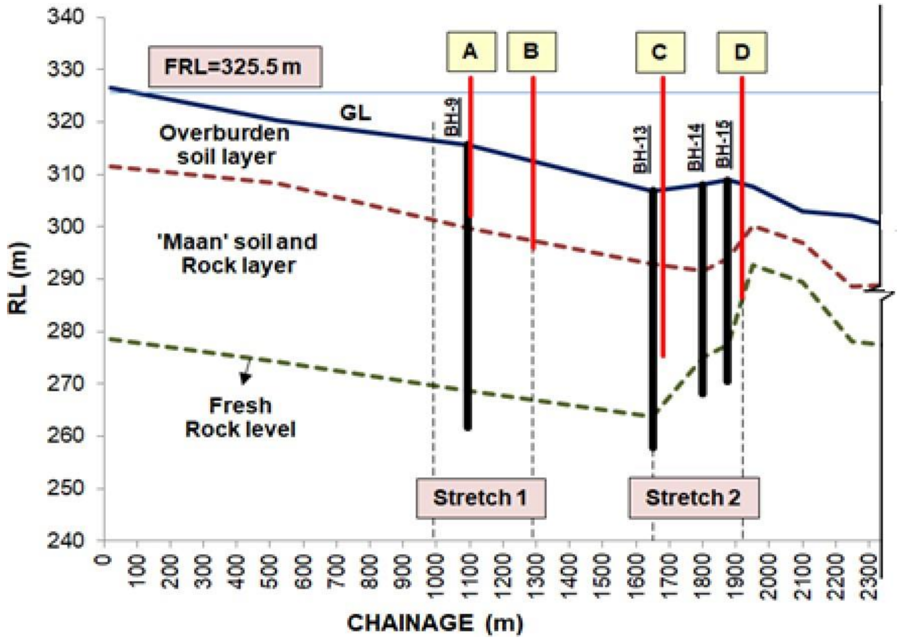

Fig. 1. 'L' section of the dam indicating cases of study

2.2 Cases Considered for Study

Combining the design dam cross-sections and foundation strata applicable at respective chainages in Stretch 1 and 2; total four cases, designated as A, B, C and D are analyzed in present study. Foundation strata of BH-9 is considered for cases A and B (Stretch 1) and that of BH-14 and BH-15 for cases C and D (Stretch 2). Details of these four cases are summarized in Table 1. Relevant portion of 'L' section of the dam indicating locations of cross-sections of four cases and that of boreholes is shown in Fig.1.

Table 1. Cases considered for study

Stretch	Case	Chainages	Deepest ground level (m)	TBL (m)	Dam height (m)	Borehole used
1	A	990 m to 1104 m	315.100	328.5	13.40	BH-9
1	B	1104 m to 1290 m	312.370	328.5	16.13	BH-9
2	C	1650 m to 1859 m	303.180	328.5	25.32	BH-14,15
2	D	1859 m to 1920 m	308.160	328.5	20.34	BH-14,15

2.4 Existing Seepage Prevention Measures

For prevention of seepage through foundation, cutoff trench (CoT) is provided in the design dam cross-sections. The CoT is not centrally aligned but slightly on upstream side. Bottom width of CoT, irrespective of its depth, is 5.0 m. CoT side slope is considered as 1(V):1(H) in overburden and 'Maan' soil while 0.25(V):1(H) in jointed/ compact and amygdaloidal basalt rock strata. As per design considerations CoT depth is adopted as 1.25 times the hydraulic head. CoT depth and bottom RL calculated based on this criterion for all cases of study are summarized in Table 2.

Table 2. CoT depth and base level

1	2	3	4	5 (4-3)	6 (1.25*5)	7 (3-6)
Case	Dam height (m)	Dam base level (m)	FRL (m)	Hydraulic Head (m)	CoT depth (m)	CoT bottom RL (m)
A	13.40	315.10	325.5	10.40	13.00	302.10
B	16.13	312.37	325.5	13.13	16.41	295.96
C	25.32	303.18	325.5	22.32	27.90	275.28
D	20.34	308.16	325.5	17.34	21.68	286.49

2.5 Method of Analysis and Material Properties

Seepage analysis of dam cross-sections for cases A, B, C and D is conducted using software PLAXIS-2D for steady state condition to establish phreatic line, seepage discharge, pore pressures and hydraulic heads in various zones of the dam and foundation. A 2D model of dam cross-section along with soil/ rock layers in foundation is modeled in the software. Upstream water level corresponding to FRL of the dam (RL 325.5 m) is adopted. Hydraulic and strength parameters of soil and rock layers along with boundary conditions are assigned. Soil/ rock properties adopted for study are given in Tables 3, 4 & 5.

Table 3. Material properties of zones in dam body

Sr. No.	Parameter	Casing	Hearting/ CoT	Filter	Rocktoe
1	Bulk density (kN/m^3)	17.708	17.685	18	20
2	Saturated density (kN/m^3)	19.277	18.546	18	20
3	Cohesion (kN/m^2)	4.41	13.93	0	0
4	Friction Angle (deg.)	29.63	16.90	30	40
5	Young's Modulus of Elasticity (MPa)	50	35	50	200
6	Poisson's ratio	0.3	0.35	0.3	0.26
7	Permeability (m/sec)	3.164×10^{-5}	5.0×10^{-9}	4.63×10^{-4}	1×10^{-3}

Table 4. Material properties of foundation in Stretch 1

Sr. No.	Parameter	OB soil	'Maan' soil	Top CB	AB	Bottom CB
1	Bulk density (kN/m^3)	18	17	19	19	19
2	Saturated density (kN/m^3)	19.277	18	20.31	20.31	20.31
3	Cohesion (kN/m^2)	4.41	51.97	0	0	0
4	Friction Angle (deg.)	29.63	39.35	34.98	34.98	34.98
5	Young's Modulus of Elasticity (MPa)	30	30	250	250	250
6	Poisson's ratio	0.3	0.3	0.25	0.25	0.25
7	Permeability (m/sec)	3.395×10^{-7}	1.05×10^{-6}	6×10^{-6}	5×10^{-6}	1.18×10^{-7}

Table 5. Material properties of foundation in Stretch 2

Sr. No.	Parameter	OB soil	Top CB	Top AB	Bottom CB	Bottom AB
1	Bulk density (kN/m^3)	18	19	19	19	19
2	Saturated density (kN/m^3)	19.277	20.31	20.31	20.31	20.31
3	Cohesion (kN/m^2)	4.41	0	0	0	0
4	Friction Angle (deg.)	29.63	34.98	34.98	34.98	34.98
5	Young's Modulus of elasticity (MPa)	30	250	250	250	250
6	Poisson's ratio	0.3	0.25	0.25	0.25	0.25
7	Permeability (m/sec)	2.16×10^{-7}	5×10^{-6}	5×10^{-6}	5×10^{-7}	1.27×10^{-7}

3 Results of Analysis for Design Dam Cross-sections

Results of analyses for cases A, B, C and D for design dam cross-section with provision of CoT (depth equal to 1.25 times hydraulic head) as seepage remedial measure, indicate that total discharge quantities are 0.7102, 0.7738, 0.2699 and 0.7169

m^3/day/m respectively. Total discharge quantity is the summation of seepage through dam body and foundation. These values are compared with permissible seepage values [6] for earth dams (Table 6).

Table 6. Permissible seepage discharge through earth dams [Ref. 6]

Case	Dam height range	Permissible Seepage Discharge (m^3/day/m)	
		Lower limit	Upper limit
A, B	10 m to 20 m	0.100	0.200
C, D	20 m to 40 m	0.200	0.400

The values indicate high seepage discharge (more than 0.7 m^3/day/m) for cases A, B and D in comparison to the permissible values. Case C indicates lower seepage value of 0.27 m^3/day/m in spite of highest hydraulic head (22.32 m) amongst all four cases. This is attributed to CoT of case C resting in deeper layers of foundation in compact basalt rock with comparatively lower permeability. It is seen that only for case C the discharge (0.2699 m^3/day/m) is less than the upper permissible limit. For all other cases the discharge is more than upper permissible limit which is not acceptable.

Fig. 2 indicates discharge vectors at centre of dam cross-section for case A. Length of flow vectors corresponds to the quantity of seepage discharge. From the flow vector plot it is inferred that, for all cases, negligible amount of seepage i.e. 0.27% to 2.10% occurs through dam body and major seepage is occurring through rock strata in foundation. High foundation seepage through rock is attributed to high permeability of top weathered/ jointed compact and amygdaloidal basalt layers as compared to overburden and ‘Maan’ soil layers. Also, lower seepage discharge occurs through soil in foundation due to presence of CoT in soil layers. Values of: (i) total seepage discharge, (ii) seepage through foundation soil and (iii) seepage through foundation rock are plotted in Fig. 3. Percentage values of seepage through rock layers are 68.19%, 66.46%, 77.18% and 84.38% for A, B, C and D respectively. Thus from the analysis it is inferred that the dam requires remedial measures to reduce foundation seepage discharge below permissible limits.

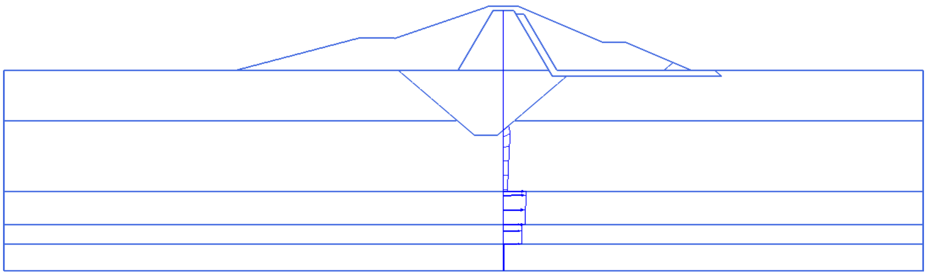

Fig. 2. Flow vectors at the centre of dam cross-section for Case A

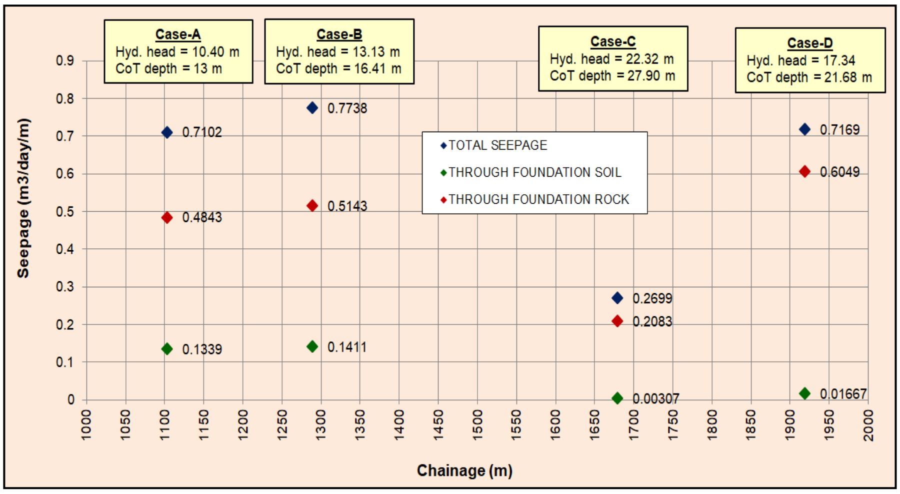

Fig. 3. Seepage discharge values for different cases of study

4 Seepage Prevention Measures

To determine the most suitable remedial measure for foundation seepage, all four cases (A, B, C and D) are analyzed in software PLAXIS 2D using different measures viz. (i) rock grouting, (ii) cutoff wall below existing CoT and (iii) upstream horizontal blanket in combination with a 6 m deep cutoff wall. Above measures are considered in addition to CoT of depth 1.25 times hydraulic head which is already present in the design. Trials are taken with different depths of cutoff wall and different lengths of horizontal blanket for optimization. For each trial, efficacy is determined by comparing discharge quantity with permissible limits. Results of all four cases with different remedial measures are discussed below.

4.1 Foundation Rock Grouting

Maximum amount of foundation seepage is occurring through jointed/ weathered compact and amygdaloidal basalt rock layers, hence as first option; remedial measure in the form of grouting of rock layers is considered. Foundation grouting aims to fill joints, fractures, fissures, bedding planes, cavities or any other openings in the rock strata; thereby reducing its permeability and preventing water losses. The post grouting permeability of all rock layers is considered as 0.5 Lugeon (5×10^{-8} m/sec).

Seepage analysis with reduced permeability of rock layers indicates that total seepage discharge reduces from 0.7102 to 0.2494 m^3/day/m for Case A, 0.7738 to 0.2742 m^3/day/m for Case B, 0.2699 to 0.0418 m^3/day/m for Case C and 0.7169 to 0.0458 m^3/day/m for Case D (Fig. 4). Thus it is seen that due to effect of grouting in rock, total seepage discharge for cases C and D falls well within the lower permissible seepage limit of 0.2 m^3/day/m. However, for cases A and B the total seepage discharge is still more than the upper permissible limit of 0.2 m^3/day/m.

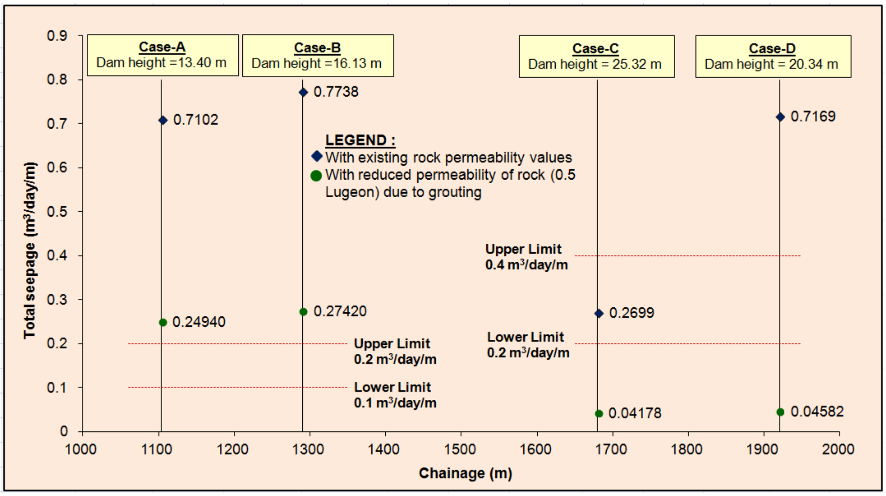

Fig. 4. Seepage discharge values with grouting of rock layer in foundation

4.2 Cutoff Wall Below CoT:

Cutoff wall of varying depths below existing CoT is considered as second remedial measure. Trials of analyses with different depths of cutoff wall are conducted to find the optimum depth corresponding to each case. Values of seepage discharge against depth of cutoff wall are plotted in Figs. 5 and 6. Results indicate that to reduce seepage discharge below the upper permissible limit of 0.2 m^3/day/m; a 35 m deep cutoff wall with bottom RL 267.1 m is required for case A and a 30 m deep cutoff wall with bottom RL 265.96 m is required for case B. With these depths, the discharge works out to be 0.1936 m^3/day/m for case A and 0.1892 m^3/day/m for case B.

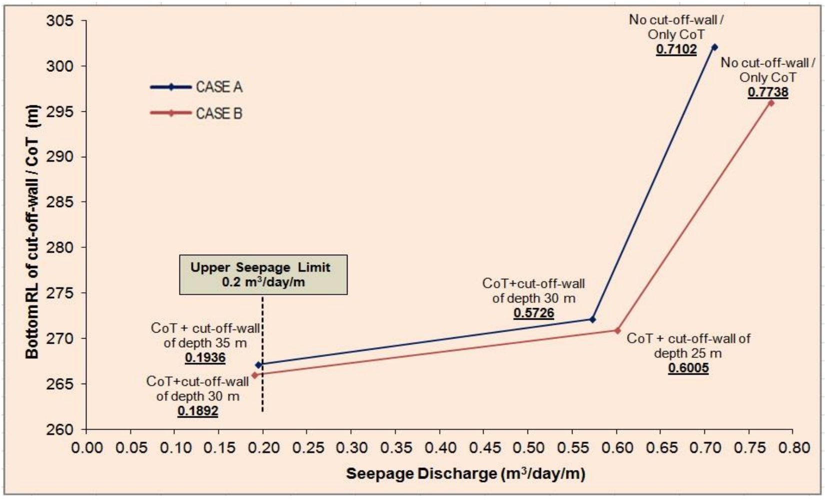

Fig. 5. Seepage discharge with cutoff walls of various depths for cases A and B

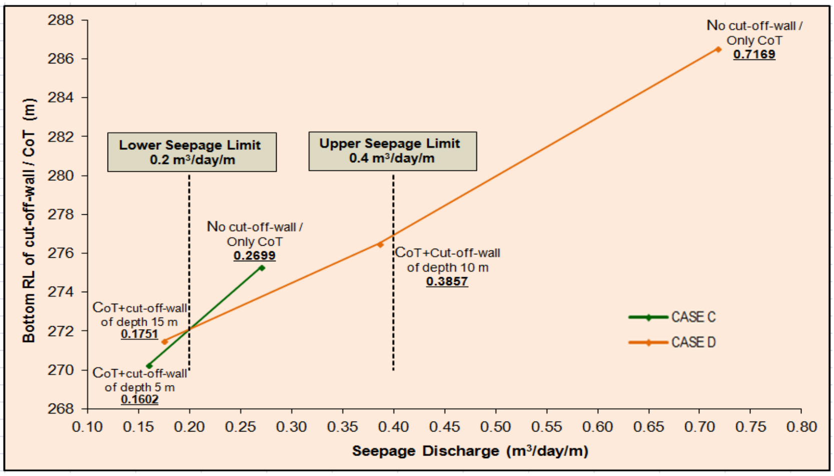

Fig. 6. Seepage discharge with cutoff walls of various depths for cases C and D

Seepage discharge (0.2699 m^3/day/m) of case C with existing CoT of depth equal to 1.25 times the hydraulic head is below the upper permissible limit of 0.4 m^3/day/m. However, to further reduce discharge below lower permissible limit of 0.2 m^3/day/m; a 5 m deep cutoff wall with bottom RL 270.28 m is required. With this depth the discharge works out to be 0.1602 m^3/day/m. Similarly for case D, to reduce seepage discharge below the upper permissible limit, a 10 m deep cutoff wall with bottom RL 276.49 m is required. With this depth the discharge works out to be 0.3857 m^3/day/m. To further reduce discharge below the lower permissible limit, a 15 m deep cutoff wall with bottom RL 271.49 m is required. With 15 m depth, the discharge works out to be 0.1751 m^3/day/m. Therefore, for all four cases, use of cutoff wall of optimized depth below existing CoT is found to be effective in reducing the seepage discharge.

4.3 Combination of Upstream Horizontal Blanket and a 6 m deep Cutoff Wall Below CoT:

Upstream horizontal blanket is intended to increase the length of seepage flow path thereby reducing the quantity of seepage. Hence the third option of remedial measure, comprising of horizontal blanket in combination with a 6 m deep cutoff wall below existing CoT is analyzed to assess its efficacy. A 1.5 m thick horizontal blanket with permeability of 5×10^{-9} m/sec (equal to that of hearting soil) is considered.

Trials are carried out for three different lengths of horizontal blanket i.e. (i) length equal to dam height, (ii) length equal to twice the dam height and (iii) length equal to 10 times the hydraulic head. Seepage discharge values for each trial corresponding to blanket length are shown in Fig. 7 for all four cases. Results indicate that even after using horizontal blanket of length 10 times the hydraulic head (104 m, 131 m, 223 m and 173 m for Case A, B, C and D respectively) the seepage discharge reduces from 0.7102 to 0.4654 m^3/day/m for Case A, 0.7738 to 0.4844 m^3/day/m for Case B, 0.2699 to 0.1185 m^3/day/m for Case C and 0.7169 to 0.4501 m^3/day/m for Case D. These values are still higher than the upper permissible limits for cases A, B and D.

Therefore, use of upstream horizontal blanket in combination with a 6 m deep cutoff wall is found to be less effective for arresting foundation seepage.

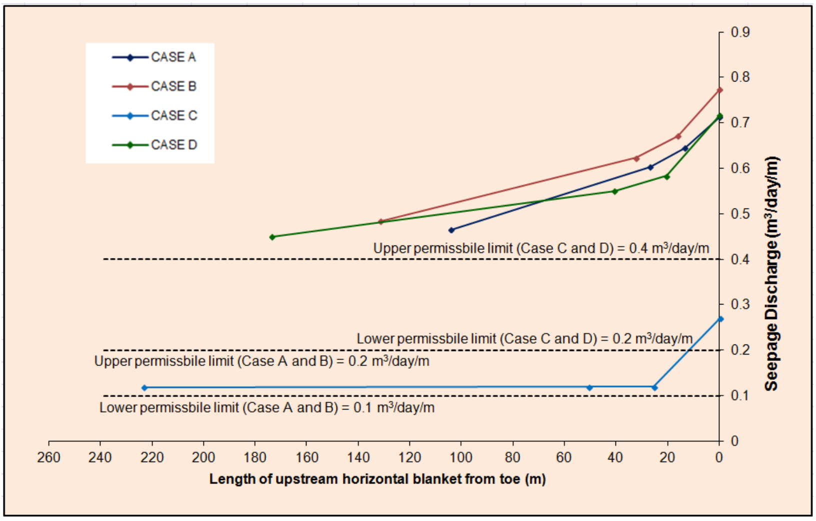

Fig. 7. Seepage discharge for horizontal blanket of various lengths

4.4 Summary of Results

Values of seepage discharge for design dam cross-section and with three remedial measures viz. (i) foundation rock grouting, (ii) cutoff wall below existing CoT and (iii) combination of upstream horizontal blanket with a 6 m deep cutoff wall for four cases viz. A, B, C and D are summarized in Table 7.

Table 7. Summary of seepage discharge values for various cases of study

Remedial measures	Seepage discharge (m^3/day/m)							
	Case A		Case B		Case C		Case D	
	Lower perm. limit=0.1 m^3/day/m Upper perm. limit=0.2 m^3/day/m				Lower perm. limit=0.2 m^3/day/m Upper perm. limit=0.4 m^3/day/m			
CoT (as per design)	0.7102		0.7738		0.2699		0.7169	
Rock grouting	0.2494		0.2742		0.0418		0.0458	
Cutoff wall	d=30 m	0.5726	d=25 m	0.6005	d=5 m	0.1602	d=10 m	0.3857
	d=35 m	0.1936	d=30 m	0.1892			d=15 m	0.1751
Combination of upstream horizontal blanket with 6 m deep cutoff wall	L=H	0.6455	L=H	0.6716	L=H	0.1202	L=H	0.5834
	L=2H	0.6028	L=2H	0.6239	L=2H	0.1196	L=2H	0.5507
	L=10h	0.4654	L=10h	0.4844	L=10h	0.1185	L=10h	0.4501

d=Depth of cutoff wall, L=Length of upstream horizontal blanket, H=Height of dam, h=hydraulic head

Results indicate that to achieve seepage discharge within the upper permissible limit, provision of cutoff wall below CoT is the best suitable solution for cases A and B. Optimized depths of cutoff wall for case A and B are estimated as 35 m and 30 m, respectively. For case C and D, both foundation rock grouting and provision of cutoff wall below CoT (depth 5 cm and 15 m for case C and D, respectively) are effective in reducing foundation seepage discharge below the lower permissible limit.

5 Conclusions and Recommendation

Seepage is an inevitable phenomenon in any earth dam which may lead to stability issues and consequent dam failure. Maximum number of earth dams worldwide have failed due to seepage related issues. To avoid failures, quantity of seepage discharge should be restricted to minimum and seepage water should be safely drained out on the downstream side without causing damages such as erosion, piping, etc. Various remedial measures such as grouting, cutoff wall below COT, upstream cutoff wall, upstream horizontal blanket, upstream slope lining, etc. are adopted for mitigation of seepage depending upon whether the seepage is through dam body or foundation. Though a number of remedial measures are available, it is important to select and optimize the suitable one to achieve best possible results. Seepage analysis by numerical modeling is a great tool for selection and optimization of remedial measures.

A case study for earth dam of Kurha-Vadhodha Islampur sinchan yojana, Maharashtra is presented in the paper. Four different cases are analyzed. Values of seepage discharge for design dam cross-sections are found to be higher than permissible values, with major seepage occurring through foundation rock. Hence, different remedial measures viz. (i) foundation rock grouting, (ii) cutoff wall below existing CoT and (iii) combination of upstream horizontal blanket with a 6 m deep cutoff wall below CoT are assessed for suitability and efficacy. Efficacy is determined in terms of reduction in seepage discharge and comparing the same with permissible values. Results indicate that foundation rock grouting is effective in reducing discharge below upper permissible limit only for cases C and D. Combination of upstream horizontal with a 6 m deep cutoff wall is also not effective to reduce seepage discharge significantly. However, cutoff wall is found to be effective for all four cases and hence cutoff wall of depth 35 m, 30 m, 5 m and 15 m for cases A, B, C and D respectively is recommended as optimized remedial measures for earth dam of Kurha - Vadodha Islampur sinchan yojana.

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