Journal of GeoEngineering, Vol. 9, No. 1, pp. 21-32, April 2014
http://dx.doi.org/10.6310/jog.2014.9(1).3

A SIMPLE METHOD FOR CALCULATING THE SEEPAGE AT THE FOUNDATION OF EMBANKMENT DAMS WITH BLANKET AND CLAY TRENCH

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ABSTRACT

Controlling the seepage at the foundation of embankment dams is of great importance. In order to reduce the seepage, various approaches are available any of which can be selected based on the condition of the foundation. The correlations recommended in the design codes for calculating the seepage, have been derived for critical conditions and mostly provide conservative values. On the other hand, some effective parameters in seepage at the foundation have not been taken into account in those correlations and thus sometimes the values obtained from them differ a lot with the real values. In this paper, a simple correlation is proposed for calculating the reduction in seepage at the foundation of embankment dams due to construction of clay trench, clay blanket or a system composed of both clay blanket and trench. In order to derive these correlations, the results from 1382 numerical analyses performed by the SEEP/W program have been used. The effect of physical and geometrical factors related to the clay blanket and trench such as the coefficient of permeability, slope of trench, width of the bottom of trench, length and thickness of the blanket have also been considered. Eventually, with regard to the effect of the mentioned factors, the results of numerical analyses have been analyzed with the SPSS 18 software. The results obtained from the suggested correlation have been compared with those obtained from the software analyses as well as internationally recommended formulas. This comparison reveals that in some cases, the values obtained from the equations proposed in those references show a considerable difference with the results of numerical modeling. However, the difference between the results of the suggested formula in this study is shown to be very small with those of numerical analyses.

Key words: Embankment dam, trench, blanket, seepage control, foundation sealing.

1. INTRODUCTION

In many cases, embankment dams are constructed on alluvial layers with high permeability and therefore controlling the seepage at the foundation of dam and calculating the discharge of water are very important. If the seepage at the foundation of embankment dams is not controlled, besides with wasting the water, in the long term use, piping might occur at the foundation causing irreversible damages to the dam. Therefore, controlling the seepage is necessary to restrict the amount of seepage, maintain the stability of the downstream backfill and prevent the corrosion of small particles underneath the foundation.

In order to control and prevent the seepage at the foundation of embankment dams several techniques can be employed. Construction of clay trench, impermeable upstream blanket, injection curtain and concrete diagrams are among these methods. Any of which have their own practical and technical limitations. For instance, the maximum depth of excavation for a clay trench is 20m (Fell *et al*. 2000). Therefore, if the foundation is too deep, a clay trench with maximum depth of 20m cannot control the seepage very well. Considering the practical limitations and condition of foundation, using any of the sealing systems or a combination of them can be right approach for controlling the seepage in the foundation of embankment dams.

Seepage analysis is one of the most substantial stages in the design process of an embankment dam. In recent years, various research methods have been applied to the study of seepage problem in dams and levees (Chahar 2004; Abdul Hussain *et al.* 2007; Amaya *et al*. 2009; Lee and Chang 2007; Zoorasna *et al*. 2008; Kacimov 2012). In order to calculate the amount of seepage passing through the foundation of embankment dams, limited number of studies has been carried out by various researchers. Also, in some reliable references and design codes a general chart is proposed, as shown in Fig. 1 for controlling the seepage in the foundation due to construction of clay trench (USBR 1987; USACE 2004). In Fig. 1, D is the depth of penetration of the trench and H_f is the thickness of dam foundation.

Equations (1 ~ 2) are recommended by USBR (1987) code for estimating the seepage in the foundation due to usage of upstream blanket.

$$\lambda = \frac{H_f}{L_2 + 0.88 H_f} \tag{1}$$

$$\lambda = \frac{H_f}{L_1 + L_2 + 0.43 H_f} \tag{2}$$

Manuscript received March 25, 2013; revised August 29, 2013; accepted September 9, 2013.
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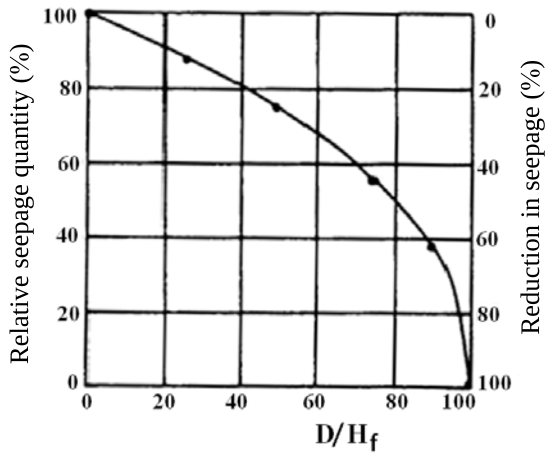


Fig. 1 Variations of seepage reduction due to construction of clay trench (USACE 1993)

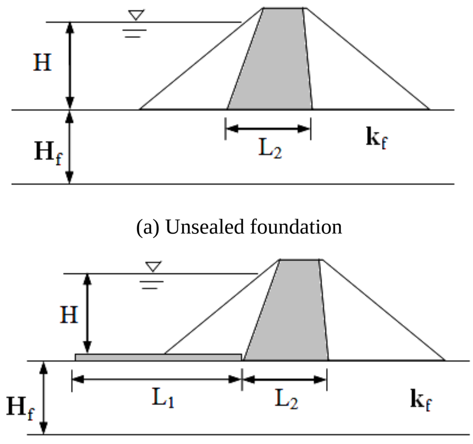


Fig. 2 Distances used in Eqs. (1) and (2)

where the λ and k_f are the coefficient of shape and coefficient of permeability, respectively. Other parameters are depicted in Fig. 2. Thus, the discharge in the unit width of the foundation can be calculated by the following equation:

$$Q = \lambda\, k_f\ H \tag{3}$$

There has been considerable number of studies on calculating the seepage at the foundation of embankment dams. In order to control the seepage within the core of two dams constructed on the Columbia River, Brown (1961) studied the impermeable blankets and drainage wells. The length of blanket in both dams was about 310 to 610m. Peterson (1968) proposed a report from the performance of the Saskatchewan River Dam in Canada where impermeable blanket was used. Goharnejad *et al*. (2010) studied the Farim-Sahra dam in Iran. Comparing the results obtained from numerical analyses with those of Bennett's equation (Bennett 1946) they noticed that the length of upstream blanket had been 150m with 0.75m thickness.

Based on the results of numerical analyses, Fakhari and Ghanbari (2013) introduced an equation to assess the discharge rate passing through vertical core embankment dams. The exiting seepage from body of the dam could be explained as following:

$$q = f\ k_f\ h \tag{4}$$

In this equation, *f* is the seepage factor which is calculated as following:

$$f = e(2.27 - 0.006W - 0.004h - 0.38 \tan \alpha) \times H^{-0.361} \tag{5}$$

where $e = (d / h)(0.3947 \tan \alpha + 0.015h - 1.3591)$

All parameters in Eq. (5) were introduced by Fakhari and Ghanbari (2013). The SI units must be used to employ this formula. Also, this equation is valid only for $\alpha \leq 45$ degrees. In this paper, the effect of clay trench and clay blanket on the control of seepage in the foundation of embankment dams has been studied and the factors effective on the reduction of seepage have been recognized. After studying all the mentioned sealing systems, a combination of both systems of clay trench and clay blanket has also been studied. Finally, by analyzing the results obtained from the software, some new correlations are proposed for calculating the seepage in the foundation of embankment dams for the above-mentioned systems.

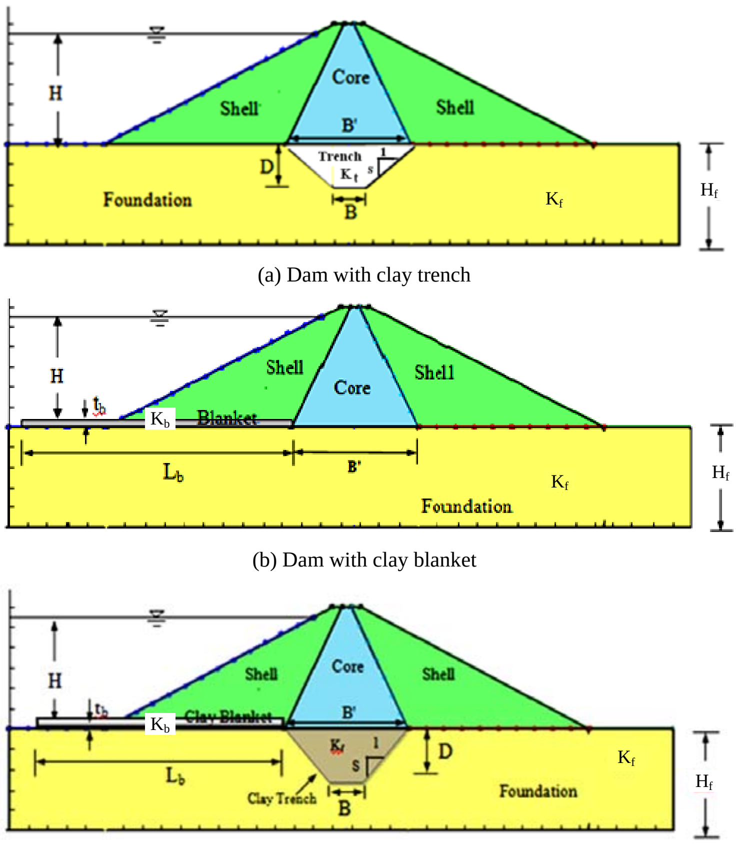
2. METHODOLOGY OF RESEARCH

In this study, a dam with geometrical properties as shown in Fig. 3 has been considered. Using the numerical analyses and having the mechanical and geometrical properties of the foundation, impermeable upstream blanket and the clay trench, the seepage reduction in the foundation has been calculated. The parameters used in analyses include: coefficient of permeability of the blanket (k_b), slope of the trench (*S*), width of the bottom of trench (*B*) and the depth of penetration of the trench (*D*).

Figure 3 illustrates the schematic dams with clay trench, blanket and combination of both of which the seepage in the foundation has been investigated. The role of mentioned parameters in reduction of seepage has also been studied. Using a multiple regression technique, a new correlation is then proposed for calculating the amount of seepage reduction for the above-mentioned systems.

In selection of the range of parameters effective in reduction of seepage at the foundation of dam, an effort has been made to take all the limitations and practical considerations into account and to generate the models with regard to the practical methods. For instance, the limitation for the minimum width of the bottom of clay trench which is 3 meters has been considered in modeling (Fell *et al*. 2000). Since in the dam projects the clay trench and blanket are usually made of the same material, the coefficient of permeability of blanket and clay trench have been considered equal in numerical analyses. The range of the physical and geometrical parameters of the foundation, clay blanket and trench are noted in Table 1.

Considering various conditions, an overall number of 1382 numerical analyses have been conducted and the results have been extracted.



(a) Dam with clay trench

(b) Dam with clay blanket

(c) Dam with clay blanket and trench

Fig. 3 Geometrical properties of the embankment dams used in analyses

Table 1 Range of the physical and geometrical parameters of the foundation and clay trench

Parameters	Foundation	Clay trench	Blanket
Permeability coefficient (m/s)	10^{-4}	$10^{-6} \sim 10^{-7}$	$10^{-6} \sim 10^{-7}$
Slope of trench	–	2 ~ 1	–
Width (m)	–	5 ~ 15	-
Length (m)	–	–	130 ~ 270
Thickness (m)	50	–	0.5 ~ 1.5

3. RESULTS OBTAINED FROM THE ANALYSES

In order to perform the analyses the SEEP/W software (2007 Edition) has been used. Considering the effect of physical and geometrical parameters in control of seepage, 1382 cross sections of the dam were analyzed. In order to mesh these models, rectangular elements with 4 nodes as well as 3-node triangular elements were employed. The results obtained from the analyses have then been compared with each other.

3.1 Sealing with Clay Trench

Figure 4 shows the reduction in seepage for various widths of the bottom of the trench. It shows that as the width of the bottom of the core increases, given all other conditions the same, the seepage in the foundation of dam decreases. In other words, decreasing the ratio of the width of the bottom of trench to the width of the bottom of core causes decrease in seepage. In soil mechanics, the following relations are known for calculating the seepage in a saturated soil medium (Das 1983):

$$Q = V\ A\,,$$

$$\text{where}\quad V = k\ i\,,\quad i = \frac{\Delta h}{\Delta l} \qquad (6)$$

where Q is the seepage in m^3/s for a section with the area A and V is the velocity of flow in m/s. Also, k is the coefficient of permeability of the medium in m/s, i is the hydraulic gradient and Δh is the head difference between two points with the length of Δl. Generally, increase in the width of the bottom of trench causes reduction in the flow from the foundation of dam. Figure 4 shows that this parameter has not been taken into account in the curves proposed by the US army corps of engineers (USACE 1993). They only considered the percentage of reduction in seepage for a constant width. Numerical analyses show that the width of the bottom of clay, B, only has minor influence in seepage at the foundation of embankment dams and the slope, S, having more significant influence on flow than the B parameter.

One of the other factors effective in seepage reduction at the foundation is the slope of the clay trench of which variations are illustrated in Fig. 5 for a constant condition. The results of analyses show that decreasing the slope of trench (S) causes decrease in seepage through the foundation of dam as well. With regard to the plotted charts, it can be concluded that this parameter is more effective than the width of the bottom of dam's core. Thus, by decreasing the slope of trench, the seepage through the foundation can be decreased more effectively.

Some engineers believe that increase in the volume of clay trench in the foundation of dam, causes more decrease in the seepage. However numerical analyses in this study show that this cannot be always true. The reason can be explained in increase of the flow velocity due to increase in the slope of the trench. Thus, it is recommended that, if possible, a trench with a smaller slope be used so that besides with decrease in the volume of the clay mass, the seepage decreases more effectively.

Figure 6 shows the reduction in seepage versus D/H_f for different permeability coefficients. According to this figure, a decrease in the coefficient of permeability and a decrease in the slope of clay trench both cause decrease in seepage at the foundation of dam.

In order to investigate the effect of the height of water in reservoir on seepage in the foundation of dam, several dams with various heights have been studied. Comparing the results shows that the seepage reduction in the foundation has been actually equal for various heights of reservoir and by varying the height of water in the reservoir no change in reduction of seepage at the foundation of dam is observed. Thus, it can be concluded that the height of water in reservoir is not effective on ratio of seepage reduction. But an increase in the height of water in reservoir leads to an increase in the amount of seepage. The results of this comparison are noted in Table 2.

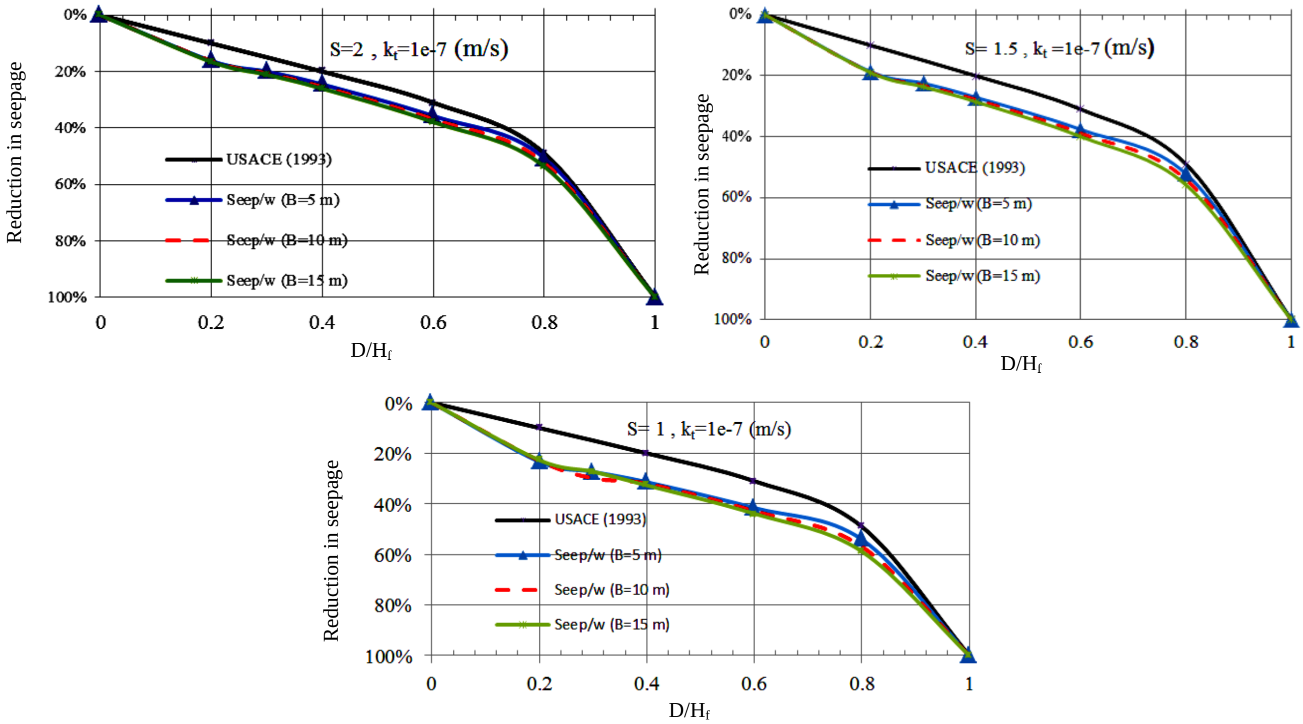


Fig. 4 Variations of reduction in the percentage of seepage at the foundation versus D/H_f

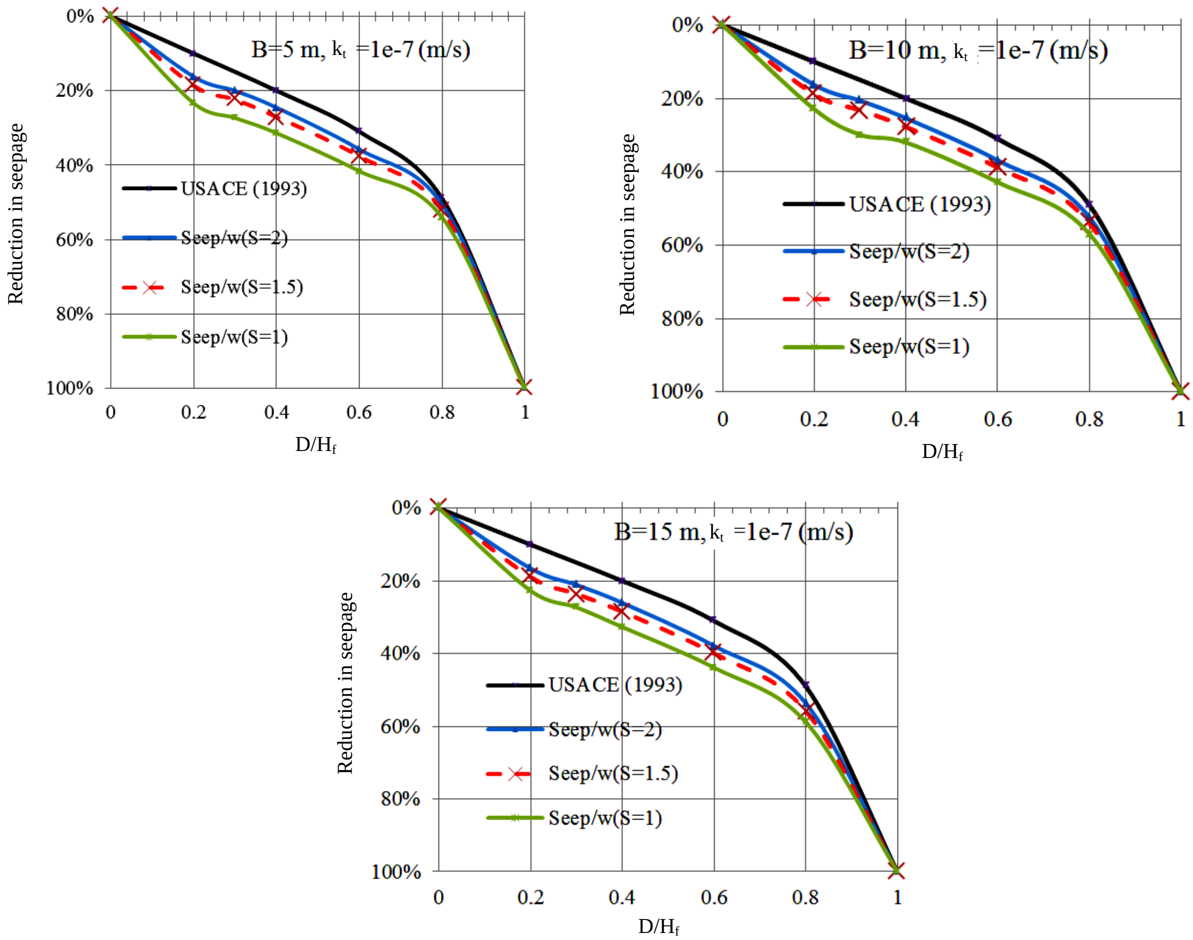


Fig. 5 Variations of the seepage reduction versus D/H_f for increase in the slope of trench

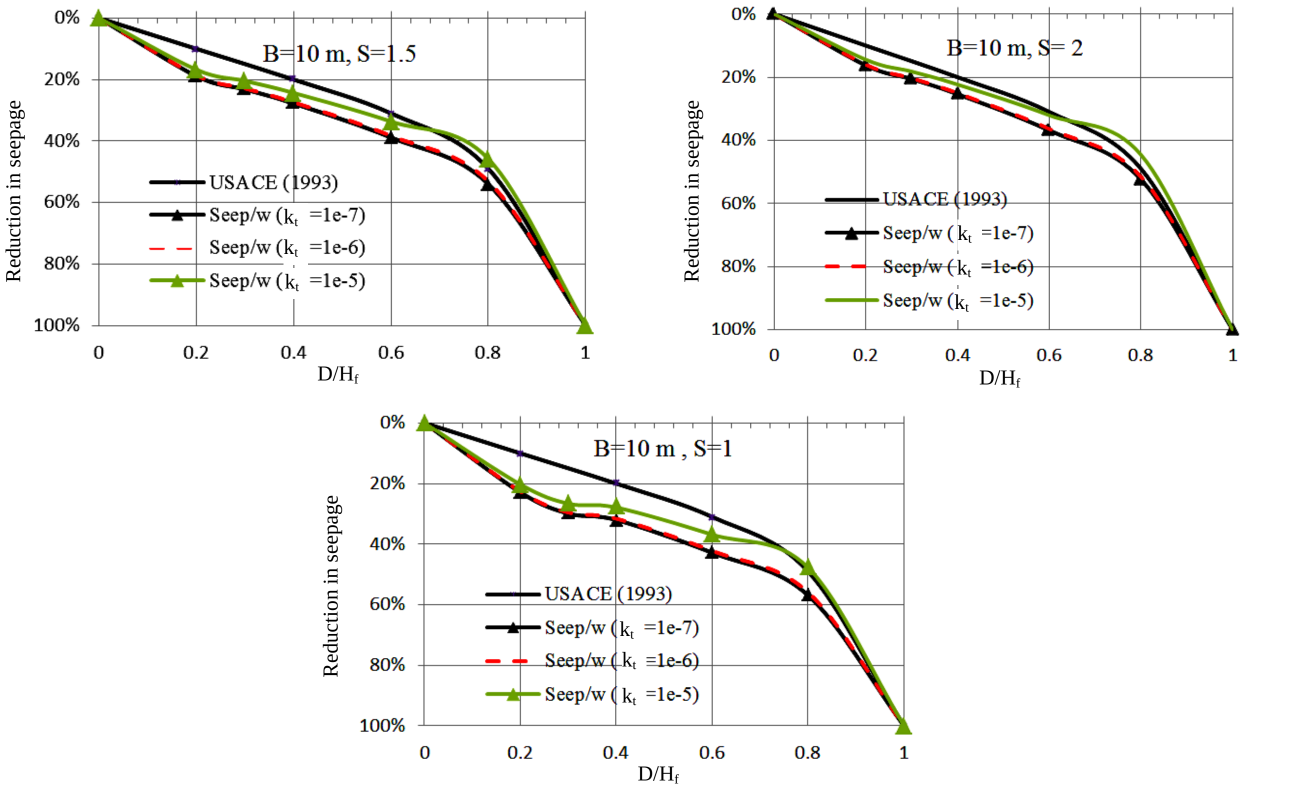


Fig. 6 Variations of seepage reduction versus D/H_f for increase in the coefficients of permeability of the trench

Table 2 The effect of the height of water in reservoir on the percentage of seepage reduction at the foundation of dam due to construction of clay trench

H (m)	D (m)	k_f (m/s)	k_t (m/s)	S	B (m)	Reduction in seepage (%)
55	15	10^{-4}	10^{-7}	1.5	10	39.40
40	15	10^{-4}	10^{-7}	1.5	10	39.37
25	15	10^{-4}	10^{-7}	1.5	10	39.38

Overall it seems that the USACE (1993) and similar codes did not take into account the effect of many factors such as slope of the trench (S), coefficient of permeability of the trench (k_t) and the width of the bottom of clay trench (B) in reduction of seepage. Thus, the curves presented by them are conservative and can lead to appropriate results only for particular conditions.

With regard to the effect of mentioned parameters in reduction of seepage at the foundation of dam due to construction of clay trench, the data from 135 models have been analyzed using the SPSS18 software. Considering the large number of variables, the multiple regression method has been used which calculates the dependent variables from the values of independent variables. Finally, various tests were performed on the results obtained from the analyses to fit the best curve through the data. The regression results are shown in Tables 3 ~ 4. In Table 4, "Beta" is the standardized regression coefficients and "B" is the unstandardized coefficient.

Table 3 The values of coefficient of correlation and variations of statistics due to the construction of clay trench

R	R^2	Adjusted R square	Std. error of the estimate
0.951	0.904	0.901	0.041892

Table 4 Standardized and unstandardized coefficients of regression for construction of clay trench

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
intercept	0.054	0.030		1.805	0.073
Log (k_f / k_t)	0.016	0.004	0.101	3.722	0.000
S	–0.052	0.010	–0.161	–5.147	0.000
B/B'	0.180	0.059	0.123	3.037	0.003
D/H_f	0.614	0.023	0.996	26.693	0.000

The results shown in Table 3 and the coefficient of determination, R equal to 0.951 imply that the regression has been of high precision. Also, using the Table 3, the following equation is suggested for calculating the reduction of seepage in the foundation of dam due to construction of clay trench:

$$R = 5.4 + 1.6\log\left(\frac{k_f}{k_t}\right) + 18\frac{B}{B'} + 61.4\frac{D}{H_f} - 5.2S \qquad (7)$$

where R is the percentage of seepage reduction in the foundation due to the effect of clay trench (%), k_f is the coefficient of permeability of the foundation in m/s, k_t is the coefficient of permeability of trench in m/s, S is the slope of clay trench, B is the width of the bottom of trench in *m*, B' is the width of the bottom of core in *m*, D is the depth of penetration of the trench in the foundation of dam in m and H_f is the thickness of dam foundation in *m*. Equation (7) shows that the reduction in seepage has a logarithmic relation with the ratio of the coefficient of permeability of the foundation to the same coefficient of trench and has a linear relation with the other parameters.

3.2 Clay Blanket

The effect of blanket in seepage reduction has been investigated in this section. Figure 7 demonstrates a sample of seepage reduction versus the variations of the length of blanket. Investigations show that for a constant thickness, increase in the length of blanket causes decrease in the percentage of seepage reduction. With regard to the Eq. (6) an increase in the length of blanket causes an increase in the length of the flow path and consequently causes a decrease in the hydraulic gradient. This causes a reduction in the velocity and thus a decrease in the discharge at the foundation of dam.

Figure 7 shows that the USBR (1987) chart for a dam with 45m width of core does not differ a lot with the chart obtained from the software but a great difference can be observed for a dam with 85m width of core. Therefore, the equation proposed by USBR (1987) results in acceptable predictions for thin cores but it is conservative for thick cores.

Figure 8 shows the effect of the blanket's thickness in reduction of seepage at the foundation. The results show an increase in the seepage reduction at the foundation due to increase in the thickness for a certain length of blanket. Therefore, for thicknesses greater than 1m the reduction in seepage is negligible. Thus, increase in the thickness of blanket more than 1m is not effective in reduction of seepage. Hence, it's suggested that the maximum thickness of blanket for sealing the embankment dam is between 0.5 to 1m.

It can be observed in Fig. 7 that the lengths of blanket less than 4 times the height of water in the reservoir ($L_b / H < 4$) have a considerable effect in reduction of seepage but higher lengths are not very effective. Therefore, the maximum length for upstream blanket is recommended as four times the height of water in the reservoir. Figure 9 shows the effect of blanket's permeability in seepage reduction. It can be observed that the effect of this parameter is much greater than the other ones so that a decrease in the permeability from 10^{-6} to 10^{-7} m/s for a blanket with 0.5m thickness causes a decrease in seepage at the foundation due to upstream blanket by 21%. Figure 10 shows the reduction in seepage for various k_f / k_b. According to this figure, reducing the seepage through foundation is largely dependent of the relative order of the permeability of the blanket and the permeability of the foundation.

In Fig. 11 a comparison is made between the USBR (1987) code and the results obtained from the software. In these figures, it can be observed that the USBR (1987) code has considered a

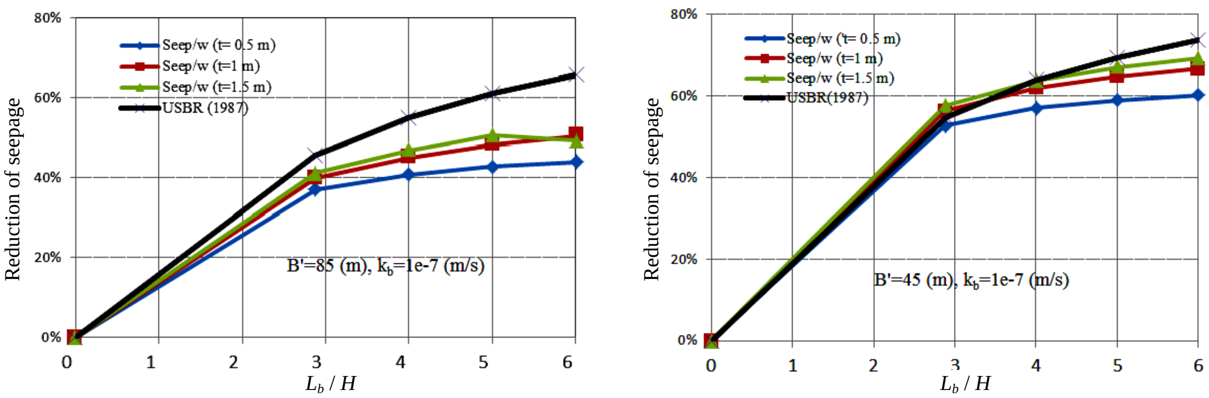


Fig. 7 Variations in the percentage of seepage reduction versus L_b / H for different thicknesses

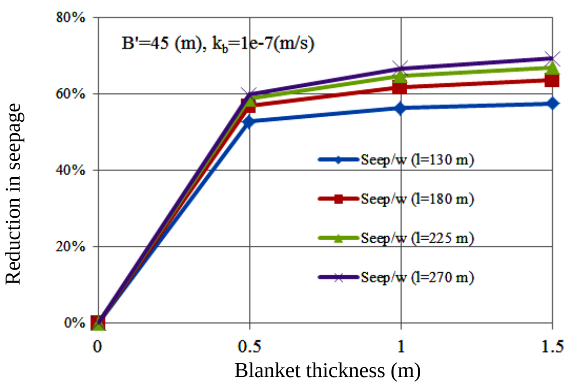


Fig. 8 Variations in seepage reduction against the increase in thickness of blanket for various lengths of blanket

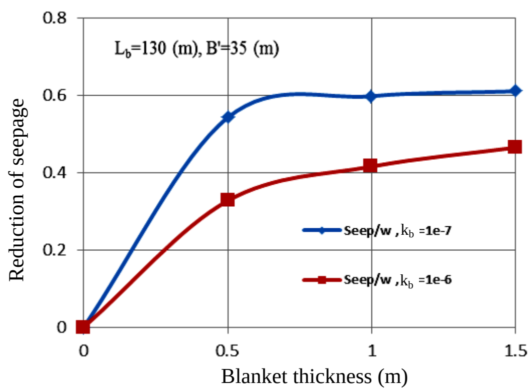


Fig. 9 Variations of seepage reduction versus the thickness of blanket for different permeability of blanket

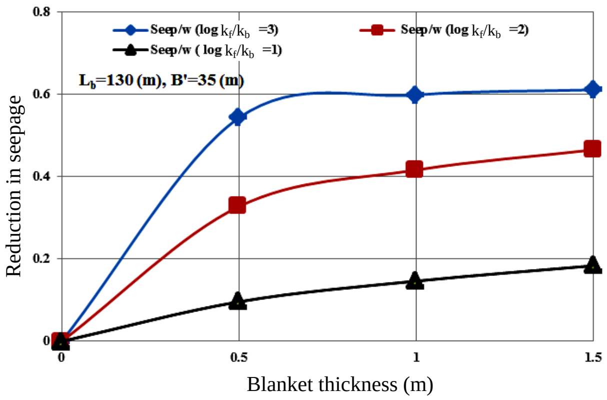


Fig. 10 Variations of seepage reduction versus the thickness of blanket for different k_f / k_b

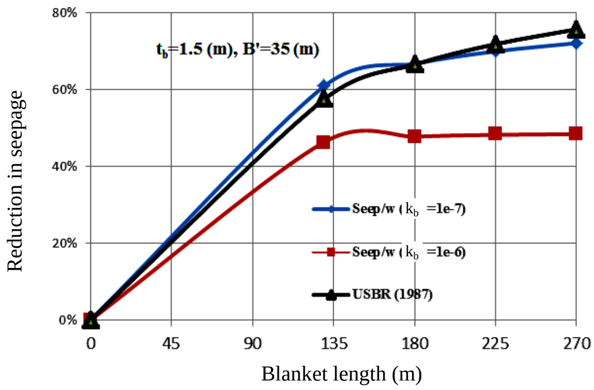


Fig. 11 Variations of seepage reduction versus increase in length of blanket and comparing it with USBR code

constant permeability of about 10^{-7} m/s. Thus, in case of using the clay with 10^{-6} m/s permeability, predicted seepage reduction by this code is different from software.

Table 5 shows the effect of height of water in reservoir on reduction of seepage. The results obtained from numerical analyses show that the height of water is changed the amount of seepage but is not effective on ratio of seepage reduction. Considering the effect of the mentioned parameters in seepage reduction at the foundation of dam due to construction of blanket, the data related to 695 models were analyzed with SPSS software. As a result, the following relation is proposed for calculating the reduction of seepage in the foundation of dam due to using the upstream blanket with thickness more than 0.5m:

$$R = 5.5 + 15.6 \log\left(\frac{k_f}{k_b}\right) - 40\frac{B'}{L_b} + 312.5\frac{t_b}{H_f} \qquad (8)$$

where R is the seepage reduction in the foundation due to the effect of blanket (%), L_b is the length of blanket in m, t_b is the thickness of blanket in m and k_b is the coefficient of permeability in m/s. Also, B' is the width of the bottom of the core of dam in m, k_f is the coefficient of permeability of foundation in m/s and H_f is the thickness of foundation in m.

Table 5 Effect of height of water in the reservoir in seepage reductions at the foundation due to construction of blanket

H (m)	k_f (m/s)	k_b (m/s)	L_b (m)	t_b (m)	Reduction in seepage (%)
55	10^{-4}	10^{-7}	220	1	55.50
40	10^{-4}	10^{-7}	220	1	55.48
30	10^{-4}	10^{-7}	220	1	55.46

3.3 Sealing with Combination of Trench and Clay Blanket

In many of the short to medium dams both trench and clay blanket are employed for sealing the dam. In this part, first the results of numerical analyses are described. Then, a new correlation for calculating the seepage in the foundation of dam when both systems of trench and clay blanket exist is proposed. The results of numerical analyses are presented in Fig. 12. Thus, the discharge decreases due to increase in the length of blanket up to 4 times the height of water in the reservoir. More increase in the length of blanket does not reduce seepage considerably. Therefore, the maximum length used for upstream blanket is recommended as 4 times the height of water in reservoir.

Also, it can be observed in Fig. 13 that if the logarithm of the ratio of the coefficient of permeability of foundation to the same coefficient of blanket in a certain length is greater than 2 (log $k_f / k_b > 2$), an increase in the depth of penetration of trench to 0.3 times the thickness of dam foundation causes a decrease in the flow passing through the foundation of dam. An increase in the penetration depth of trench up to 0.8 times of the thickness of dam foundation does not change the amount of seepage but an increase in the depth of penetration more than 0.8 times the thickness of dam foundation causes a decrease in seepage again.

Figure 14 shows the effect of change in the slope of trench in the amount of flow. The results of analyses show that a decrease in the slope of clay trench (S) causes a decrease in seepage at the foundation of dam. Figure 15 shows the effect of the coefficient of permeability of blanket in seepage reductions at the foundation. It can be observed that the effect of this parameter is much greater than other parameters so that a decrease in permeability from 10^{-6} to 10^{-7}m/sec for a blanket with 270m length and D/H_f equal to 0.2 causes an increase in the percentage of reduction in seepage at the foundation due to application of clay blanket and trench by 15%. The percentage of reduction in seepage for various heights of water in reservoir is noted in Table 6.

With regard to the effect of mentioned parameters in reduction of seepage at the foundation of dam, the data related to 552 models have been analyzed using the SPSS18 software. Finally, several tests have been carried out on the results obtained from these analyses to fit the best curve through the data. Tables 7 ~ 8 show the results of regression.

Using Table 8, the following correlation is proposed for calculating the seepage reduction in the foundation for a dam with both clay trench and blanket:

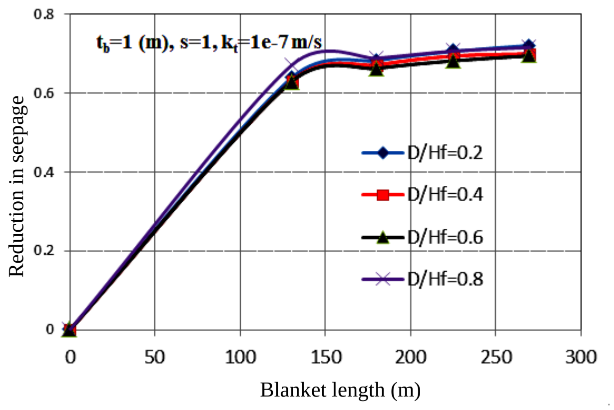


Fig. 12 Variations of seepage reduction versus increase in length of blanket for various depths of penetration of trench

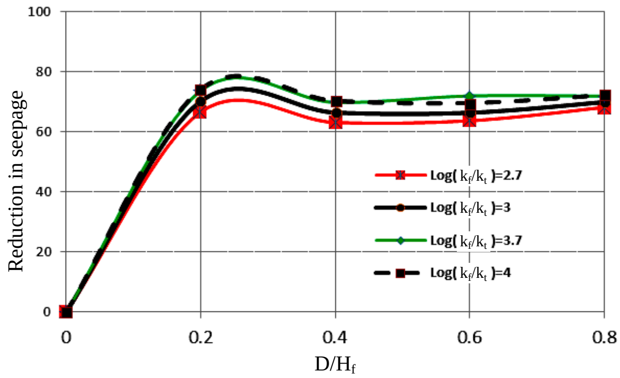


Fig. 13 Variations of seepage reduction in the foundation D / H_f for different k_f / k_t

$$R = 29.7 - 7.8S + 13.6 \log \frac{k_f}{k_t} + 515.8 \frac{t_b D}{H_f^2} - 34.3 \frac{BB'}{L_b^2} \quad (9)$$

where R is the percentage of reduction in seepage at the foundation due to the combined effect of blanket and clay trench (%), L_b is the length of blanket in m, t_b is the thickness of blanket in m, k_b is the coefficient of permeability of blanket in m/s, S is the slope of clay trench, D is the depth of penetration in m and B is the width of bottom of trench in m. Also, H_f is the thickness of dam foundation in m, k_f is the coefficient of permeability of foundation in m/s and B' is the width of bottom of core in m.

With regard to the Eq. (9), it's obvious that the amount of reduction in seepage has a non-logarithmic relation with the ratio of the coefficient of permeability of foundation to the same ratio of clay trench or blanket and it has a non-logarithmic relation with the other parameters. Thus, the amount of discharge in the unit width of the foundation of dam due to usage of any of the mentioned systems including clay trench, blanket or both of them can be calculated from the following correlation:

$$q = (1 - R)\left(\frac{H_f}{B' + 0.88H_f}\right) k_f H \quad (10)$$

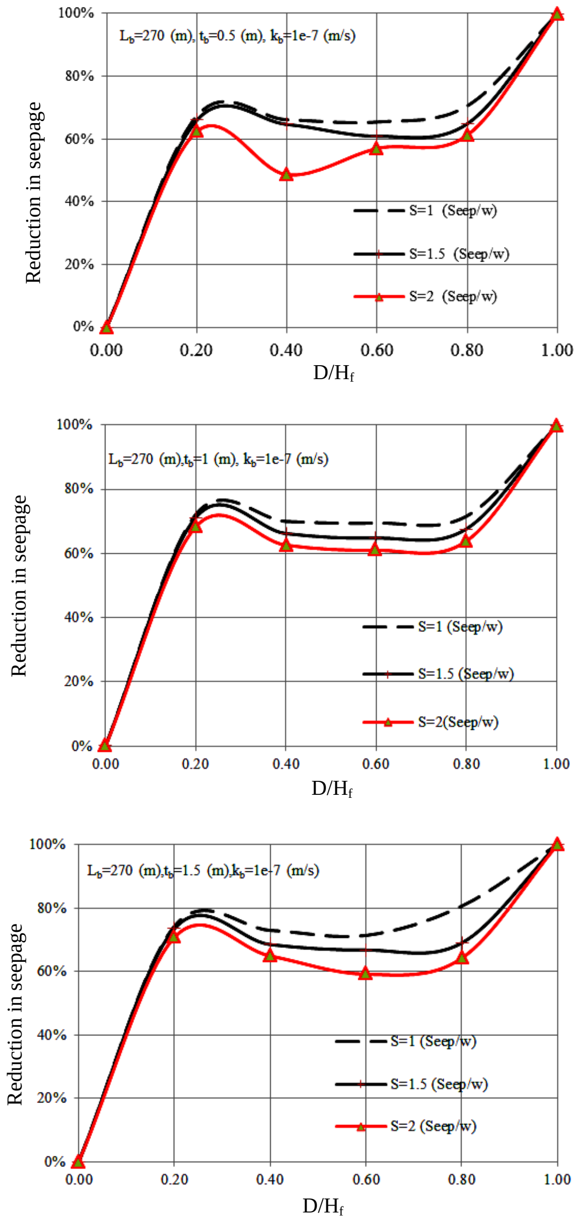


Fig. 14 Variations of seepage reduction versus D/H_f for different t_b

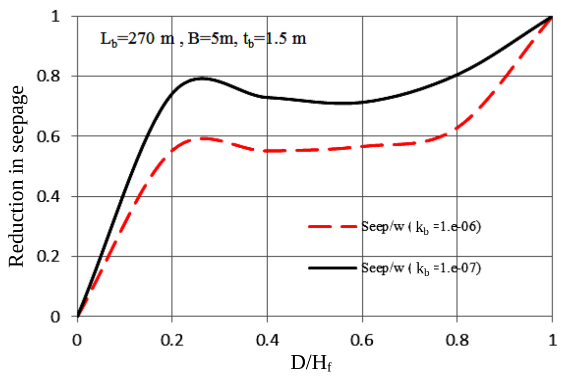


Fig. 15 Variations of the percentage of seepage reduction versus D/H_f for different permeability coefficient of blanket

Table 6 Effect of the height of water in reservoir in reduction of seepage at the foundation for a dam with clay trench and blanket

H (m)	D/H_f	k_f (m/s)	k_t (m/s)	L_b (m)	t_b (m)	B (m)	S	Reduction in seepage (%)
55	0.4	10^{-4}	10^{-7}	225	1.7	15	1	73.56
40	0.4	10^{-4}	10^{-7}	225	1.7	15	1	73.48
25	0.4	10^{-4}	10^{-7}	225	1.7	15	1	73.49

Table 7 Coefficient of correlation and variation of statics for a dam with clay trench and blanket

R	R^2	Adjusted R square	Std. error of the estimate
0.877	0.769	0.768	0.0441363

Table 8 Standardized coefficient of regression and unstandardized regression for a dam with clay trench and blanket

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
Constant	0.297	0.012		23.785	0.0
S	–0.078	0.005	–0.301	–14.548	0.0
Log (k_f / k_t)	0.136	0.004	0.741	36.074	0.0
$t_b\ D/H_f^2$	5.158	0.322	0.347	16.008	0.0
$B\ B'/L_b^2$	–0.343	0.124	–0.060	–2.762	0.006

4. COMPARING THE RESULTS OF THE SUGGESTED FORMULA WITH OTHER REFERENCES

Table 9 shows a comparison between the percentage of seepage reduction in the foundation of dam due to construction of clay trench calculated from the suggested formula in this study with the results obtained from the SEEP/W software as well as the USACE (1993).

It can be observed that the suggested formula provides an acceptable estimation for the reduction of seepage due to construction of clay trench. Also, it can be observed that the values calculated based on the USACE (1993) are on the conservative side for the seepage reduction in the foundation of embankment dams because they did not consider the width of the bottom of trench, slope of trench and permeability of trench in their formulas which leads to conservative and uneconomical designs.

Tables 10 ~ 11 show the comparison between the percentages of seepage reduction in the foundation when blanket exists obtained from the suggested method, results of SEEP/W software, the correlation suggested by Bennett (1946) and USBR (1987) code. It can be observed that the suggested formula gives an appropriate estimation of the reduction in seepage due to construction of upstream blanket. Also, it can be observed that if the logarithm of the ratio of the coefficient of permeability of foundation to the same value of blanket is smaller than 2, the results of USBR (1987) show a great difference with those obtained from the software. Table 11 shows that the relation proposed by Bennett (1946) does not provide an appropriate estimation for seepage reduction at the foundation and in some conditions it differs a lot with the software results.

Table 9 Comparison of seepage reduction due to clay trench calculated from the suggested formula, SEEP/W software and USACE (1993)

No.	D (m)	H_f (m)	D/H_f	B/B'	S	k_f (m/s)	k_t (m/s)	Log (k_f / k_t)	Reduction in seepage (%) (SEEP/W)	Proposed formula		USACE (1993)	
										Reduction in seepage (%)	Error (%)	Reduction in seepage (%)	Error (%)
1	6	30	0.20	0.14	1.50	10^{-4}	10^{-7}	3	15.40	17.25	1.85	10.00	5.40
2	20	70	0.29	0.27	1.00	10^{-4}	10^{-7}	3	26.68	27.45	0.77	15.00	11.68
3	15	70	0.21	0.45	1.00	10^{-4}	10^{-7}	3	23.06	26.34	3.28	10.00	13.06
4	10	60	0.17	0.17	1.25	10^{-4}	10^{-7}	3	18.49	16.93	–1.56	7.00	11.49
5	25	60	0.42	0.09	1.00	10^{-4}	10^{-7}	3	32.14	32.22	0.08	22.00	10.14
6	22.5	90	0.25	0.18	1.00	10^{-4}	10^{-7}	3	24.21	23.62	–0.59	12.50	11.71
7	22.5	90	0.25	0.18	1.00	10^{-4}	10^{-6}	2	23.91	22.02	–1.89	12.50	11.41
8	11.66	90	0.13	0.36	1.50	10^{-4}	10^{-6}	2	14.48	15.30	0.82	3.00	11.48
9	16.25	90	0.18	0.19	2.00	$2.5 \cdot 10^{-4}$	$3.7 \cdot 10^{-7}$	2.83	14.90	13.99	–0.91	8.00	6.90
10	16.25	90	0.18	0.19	2.00	$2.5 \cdot 10^{-4}$	$3.7 \cdot 10^{-8}$	3.83	14.93	15.59	0.66	8.00	6.93

Table 10 Comparison between the reductions of seepage due to blanket obtained from different methods

No.	H_f (m/s)	t_b (m)	t_b/H_f	B' (m)	L_b (m)	B'/L_b	k_f (m/s)	k_b (m/s)	Log (k_f / k_b)	Reduction in seepage (%) (SEEP/W)	Proposed formula		USBR (1987)	
											Reduction in seepage (%)	Error (%)	Reduction in seepage (%)	Error (%)
1	45	0.5	0.011	95	155	0.613	10^{-4}	10^{-7}	3.00	43.9	31.26	–12.64	50.03	6.13
2	30	0.5	0.017	95	130	0.731	10^{-4}	10^{-7}	3.00	42.5	28.28	–14.22	48.97	6.47
3	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-7}	3.00	44.3	32.99	–11.31	53.82	9.52
4	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-6}	2.00	20.5	17.39	–3.11	53.82	33.32
5	30	0.5	0.017	95	200	0.475	10^{-4}	10^{-7}	3.00	46.1	38.51	–7.59	60.57	14.47
6	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-7}	3.00	44.30	32.99	–11.31	53.82	9.52
7	30	0.5	0.017	95	200	0.475	10^{-4}	10^{-7}	3.00	46.10	38.51	–7.59	60.57	14.47
8	35	1.25	0.036	45	150	0.300	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	52.70	41.27	–11.43	63.91	11.21
9	35	1.4	0.040	45	145	0.310	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	53.10	42.20	–10.90	63.03	9.93
10	35	1.4	0.040	45	170	0.265	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	54.20	44.02	–10.18	67.05	12.85
11	35	1.4	0.040	45	220	0.205	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	55.30	46.43	–8.87	72.93	17.63
12	35	1.7	0.049	45	150	0.300	$7.7{\cdot}10^{-5}$	$4.4{\cdot}10^{-8}$	3.24	65.00	59.27	–5.73	63.91	–1.09
13	35	1.5	0.043	45	150	0.300	$7.7{\cdot}10^{-5}$	$4.4{\cdot}10^{-8}$	3.24	64.80	57.48	–7.32	63.91	–0.89
14	45	0.5	0.011	65	200	0.325	10^{-4}	$8.5{\cdot}10^{-7}$	2.07	22.60	28.27	5.67	63.21	40.61
15	45	1.0	0.022	65	200	0.325	10^{-4}	$8.5{\cdot}10^{-7}$	2.07	30.65	31.75	1.10	63.21	32.56

Table 11 Comparison between the seepage reductions due to blanket obtained from different methods

No.	H_f (m/s)	t_b (m)	t_b / H_f	B' (m)	L_b (m)	B'/L_b	k_f (m/s)	k_b (m/s)	Log (k_f / k_b)	Reduction in seepage (%) (SEEP/W)	Proposed formula		Bennett's equation	
											Reduction in seepage (%)	Error (%)	Reduction in seepage (%)	Error (%)
1	45	0.5	0.011	95	155	0.613	10^{-4}	10^{-7}	3.00	43.9	31.26	–12.64	38.78	–5.12
2	30	0.5	0.017	95	130	0.731	10^{-4}	10^{-7}	3.00	42.5	28.28	–14.22	43.68	1.18
3	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-7}	3.00	44.3	32.99	–11.31	43.68	–0.62
4	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-6}	2.00	20.5	17.39	–3.11	71.04	50.54
5	30	0.5	0.017	95	200	0.475	10^{-4}	10^{-7}	3.00	46.1	38.51	–7.59	43.68	–2.42
6	30	0.5	0.017	95	155	0.613	10^{-4}	10^{-7}	3.00	44.30	32.99	–11.31	43.68	–0.62
7	30	0.5	0.017	95	200	0.475	10^{-4}	10^{-7}	3.00	46.10	38.51	–7.59	43.68	–2.42
8	35	1.25	0.036	45	150	0.300	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	52.70	41.27	–11.43	31.34	–21.36
9	35	1.4	0.040	45	145	0.310	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	53.10	42.20	–10.90	30.13	–22.97
10	35	1.4	0.040	45	170	0.265	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	54.20	44.02	–10.18	30.13	–24.07
11	35	1.4	0.040	45	220	0.205	10^{-3}	$4.5{\cdot}10^{-6}$	2.35	55.30	46.43	–8.87	30.13	–25.17
12	35	1.7	0.049	45	150	0.300	$7.7{\cdot}10^{-5}$	$4.4{\cdot}10^{-8}$	3.24	65.00	59.27	–5.73	12.24	–52.76
13	35	1.5	0.043	45	150	0.300	$7.7{\cdot}10^{-5}$	$4.4{\cdot}10^{-8}$	3.24	64.80	57.48	–7.32	12.93	–51.87
14	45	0.5	0.011	65	200	0.325	10^{-4}	$8.5{\cdot}10^{-7}$	2.07	22.60	28.27	5.67	55.82	33.22
15	45	1	0.022	65	200	0.325	10^{-4}	$8.5{\cdot}10^{-7}$	2.07	30.65	31.75	1.10	47.18	16.53

Another comparison has been made in Table 12 between the percentage of seepage reduction in the foundation when blanket and clay trench are used calculated from the suggested formula with those obtained from the SEEP/W software. It can be observed that the results of suggested relation have a little difference with those obtained from numerical analyses. Thus, the suggested relation provides an appropriate estimation of the seepage reductions due to application of blanket and clay trench and can be used for initial estimation of seepage in the foundation of embankment dams.

Table 12 Comparison between the seepage reduction due to clay trench and blanket obtained from different methods

No.	D (m)	H_f (m)	B (m)	B (m)'	L_b (m)	t_b (m)	S	k_f (m/s)	k_t (m/s)	Log (k_f / k_t)	t_bD / H_f^2	BB'/L_b^2	Software (SEEP/W)	Proposed formula	
													Reduction in seepage (%)	Reduction in seepage (%)	Error (%)
1	10	30	15	95	170	0.5	2	$1.00{\cdot}10^{-4}$	$1.00{\cdot}10^{-8}$	4.00	0.006	0.049	60.60	69.67	9.07
2	10	30	15	65	130	0.9	2.5	$1.00{\cdot}10^{-4}$	$2.20{\cdot}10^{-7}$	2.66	0.010	0.058	39.65	49.52	9.87
3	10	30	15	65	185	0.9	2.5	$1.00{\cdot}10^{-4}$	$2.20{\cdot}10^{-7}$	2.66	0.010	0.028	42.53	50.52	7.99
4	15	30	5	65	145	0.5	2	$1.00{\cdot}10^{-4}$	$1.00{\cdot}10^{-7}$	3.00	0.008	0.015	59.60	58.67	–0.93
5	15	30	20	65	145	0.5	1.5	$1.00{\cdot}10^{-4}$	$1.00{\cdot}10^{-7}$	3.00	0.008	0.062	61.74	60.98	–0.76
6	15	40	5	65	200	0.9	2	$3.30{\cdot}10^{-3}$	$1.00{\cdot}10^{-6}$	3.52	0.008	0.008	67.41	66.03	–1.38
7	10	40	5	65	200	0.9	3	$3.30{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	3.12	0.006	0.008	62.84	51.36	–11.48
8	10	40	25	65	200	0.9	2	$3.30{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	3.12	0.006	0.041	63.62	58.05	–5.57
9	20	40	25	65	200	0.9	1	$3.30{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	3.12	0.011	0.041	68.17	68.75	0.58
10	20	40	25	65	250	0.9	1	$3.30{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	3.12	0.011	0.026	70.03	69.25	–0.78
11	20	40	5	65	250	0.9	1.5	$3.30{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	3.12	0.011	0.005	68.41	66.06	–2.35
12	10	35	5	45	230	1.25	2	$1.00{\cdot}10^{-3}$	$1.00{\cdot}10^{-6}$	3.00	0.010	0.004	70.50	60.02	–10.48
13	10	35	15	45	230	1.25	1.5	$1.00{\cdot}10^{-3}$	$1.00{\cdot}10^{-6}$	3.00	0.010	0.013	70.95	63.63	–7.32
14	10	35	15	45	230	1.25	1.5	$1.00{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	2.60	0.010	0.013	64.49	58.21	–6.28
15	15	35	15	45	230	1.25	1	$1.00{\cdot}10^{-3}$	$2.50{\cdot}10^{-6}$	2.60	0.015	0.013	66.93	64.75	–2.18
16	15	35	15	45	150	1.25	1	$1.00{\cdot}10^{-3}$	$2.50{\cdot}10^{-7}$	3.60	0.015	0.030	70.74	77.75	7.01
17	10	35	5	45	220	1.7	2	$1.00{\cdot}10^{-3}$	$4.50{\cdot}10^{-7}$	3.35	0.014	0.005	74.05	66.61	–7.44
18	20	35	5	45	220	1.7	1	$1.00{\cdot}10^{-3}$	$4.50{\cdot}10^{-7}$	3.35	0.028	0.005	76.46	81.57	5.11
19	15	35	15	45	220	1.7	1	$1.00{\cdot}10^{-3}$	$4.50{\cdot}10^{-7}$	3.35	0.021	0.014	75.67	77.68	2.01
20	15	35	15	45	220	1.7	1	$1.00{\cdot}10^{-3}$	$5.70{\cdot}10^{-7}$	3.24	0.021	0.014	75.17	76.28	1.11

5. CONCLUSIONS

The results of numerical analyses for the clay trench show that the amount of passing discharge through the foundation of dam increases with increase in the ratio of the width of the bottom of trench to the width of the bottom of core. Also, controlling the seepage and reducing it can lead to narrower slopes for the trench. Studies show that decreasing the coefficient of permeability causes decrease in the seepage at the foundation. However, some design codes such as the USACE (1993) have suggested a conservative chart for this purpose.

The results of this study show that the optimum thickness for the blanket ranges from about 0.5m to the maximum value of 1m. Also, the appropriate length of clay blanket is about four times the height of water in the reservoir.

With regard to the importance of the mentioned parameters in decreasing seepage, a correlation (Eq. (7)) is proposed for initial designs and also for situations where a quick estimation of seepage reduction in the foundation due to construction of clay trench is required. If clay blanket is used as the sealing system Eq. (8) can be used for calculating the percentage of seepage reduction. If a single system of sealing cannot control the seepage through the foundation effectively, combined system of blanket and clay trench can be used for reducing the seepage. In this case, Eq. (9) can be used.

Comparing the results calculated from these correlations with those obtained from SEEP/W software and reliable references shows that the suggested correlations in this study provide an appropriate estimation of the seepage reduction in the foundation with regard to the type of sealing system used. The results of these formulas are more precise compared with the curves and correlations suggested in other references. Overall the suggested correlations in this paper are capable of predicting an acceptable estimation of reduction in seepage at the foundation and they can be used for initial designs of sealing systems for embankment dams.

REFERENCES

Abdul Hussain, I.A., Dashvap, D., and Hari Prasad, K.S. (2007). “Seepage modeling assisted optimal design of a homogeneous earth dam: Procedure evolution.” *Journal of Irrigation and Drainage Engineering*, **133**(2), 116–130.

Amaya, P.J., Massey-Norton, J.T., and Stark, T.D. (2009). “Evaluation of seepage from an embankment dam retaining fly ash.” *Journal of Performance of Constructed Facilities*, **23**(6), 406–414.

Bennett, P.T. (1946). “The effect of blanket on seepage through pervious foundation.” ASCE Transactions, **3**, 52–61.

Brown, F.S. (1961). “Service behavior of blanket as a method of sealing dams." *Proceeding of the 7th International Congress on Large Dams*, ICLD - 61, Rome, 301−325.

Chahar, B.R. (2004). "Determination of length of a horizontal drain in homogeneous earth dams." *Journal of Irrigation and Drainage Engineering*, **130**(6), 530−536.

Das, B.M. (1985). *Advanced Soil Mechanics*. McGraw Hill.

Fakhari, A. and Ghanbari, A. (2013). "A simple method for calculating the seepage from earth dams with clay core." *Journal of GeoEngineering*, TGS, **8**(1), 27−32.

Fell, R., Macgregor, J.P., and Stapledon, D.H. (2000). *Geotechnical Engineering of Embankment Dams*, Balkema.

Goharnejad, H., Noury, M., Noorzad, A., Shamsaie, A., and Goharnejad A. (2010). "The effect of clay blanket thickness to prevent seepage in dam reservoir." *International Journal of Environmental Sciences*, **4**(6), 556−565

Peterson, R. (1968). "Lessons learned from practice of P.F.R.A. including stability problems on clay shales." *Delacourte Press*, New York, 531.

Kacimov, A.R. (2012). "Darcian seepage through a parallelogrammic ramp: Toth's model revisited." *Journal of Irrigation and Drainage Engineering*, **138**(4), 377−381.

Lee, H.W. and Chang, P.W. (2007) "Correlation between the laboratory and in-situ permeabilities for the embankments." *Journal of Civil Engineering*, KSCE, **11**(1), 1−5.

SEEP/W (2007). *Seepage Modeling with SEEP/W*. Geo-Slope International Ltd, Calgary.

USACE (1993). *Seepage Control in Earth Foundation*, EM 1110-2-1901, U.S. Army corps of Engineering, Washington, D.C.

USACE (2004). *Seepage Control*, *EM 1110-2-2300*, U.S. Army corps of Engineering, Washington, D.C.

USBR (1987). *Embankment Dams*, *Chapter 5*, *Seepage analysis*, U.S. Department of the Interior, Bureau of Reclamation, Washington, D.C.

SPSS18 Software. *IBM SPSS Software. Predictive Analytics Software and Solutions*. Version 18.0 (SPSS)

Zoorasna, Z., Hamidi, A., and Ghanbari, A. (2008). "Mechanical and hydraulic behavior of cut off-core connecting systems in earth dams." *Electronic Journal of Geotechnical Engineering*, **13**, Bund. K.