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FEM Based Seepage Analysis through Earth Dam

MD. MAHMUD SAZZAD[1], MRINMOY ROY[2], MD. SAIDUR RAHMAN[1]
[1]Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh
[2] International Resource Group Development Services Ltd., Bangladesh
Email: mmsruet.research@gmail.com, mrinmoy9119@gmail.com, saidur78.ruet09@gmail.com

Abstract: Measurement of seepage through hydraulic structures is very important from their safety point of view. In case of a dam made of earth, seepage generally occurs through the dam. Due to excessive seepage, scouring and piping may occur which may lead to ultimate failure of a dam. Consequently, seepage investigation is very important in designing any hydraulic structures. In this study, seepage through the dam body has been investigated numerically and analytically for various parameters of dam and different conditions such as mesh shape and size, shape of internal clay core, upstream and downstream slope angle, permeability of base material etc. For this purpose, different geometric models of dams have been prepared and discharge rate corresponding to each geometric model have been analysed. A comparison between the numerical and analytical results has been made. Effect of various parameters and conditions on seepage has been studied. Computer program Seep/W (2007) has been used for the investigation of seepage. From the study, it is found that variation in seepage is dominant up to mesh number of 150 and beyond that, the difference is not significant. Mesh shape and size has negligible effect on the seepage. Upstream and downstream slope angles have no effect on seepage when clay core is provided. Seepage is independent of base permeability when core is not used. Base type (pervious or impervious) affects the seepage for larger values of hydraulic conductivity when internal clay core is provided. When hydraulic conductivity is very small, base type has no effect on seepage.

Keywords: *Earth Dam, Clay Core, Seepage, Numerical Analysis, Finite Element Method*

Introduction:

Earth dam is probably the oldest type of dam. An earth dam is generally constructed with locally available earth with high compaction. Earth dam is an economical hydro-engineering structure. Earth dams are constructed for various purposes, such as the protection of living beings, properties, etc. from flood; storing water for irrigation, water supply and energy generation. Therefore, it is very important to investigate the effect of water on earth dam. According to Foster and Fell (1999), 25% of dam failure has been occured due to wash out of fine granules from the dam body or dam foundation. There are various methods for calculating the discharge rate (i.e., seepage) through the dam body. Using analytical solutions, the seepage through an earth dam can be estimated. Many researchers such as Schaffernak (1917), Casagrande (1937), Stello (1987), Rezk and Senoon (2011) etc. have used analytical methods to calculate the seepage through the dam body. However, analytical methods require many assumptions and only simple and straight forward seepage problem can be solved.

Apart from this analytical approach, numerical approaches such as finite element method, finite difference method and finite volume method are also used to determine the seepage through the earth dam. Among these numerical methods, finite element method is the most popular and widely used method.

An important advantage of using finite element method (FEM) in seepage analysis is that the solution of seepage problem is faster and complex seepage problems can be solved. Several authors have used FEM to solve the seepage problem of earth dam (Papagianakis and Fredlund, 1984; Lam et al, 1988; Potts and Zdravkovic, 1999). Fakhari and Ghanbari (2013) numerically analyzed almost 600 geometric models for embankment dams with clay core using Seep/W. Salmasi and Jafari (2013) numerically analyzed 28 assumed models with impervious base, varying upstream reservoir height, upstream and downstream slope using steady state two dimensional flow through homogeneous earth dam in Seep/W. Giglu and Zeraatparv (2012) presented a simplified method to estimate seepage through earth dams under steady-state conditions. The numerical results illustrated that the complete solution of a saturated and unsaturated flow problem provides better information relative to positive and negative pore-water pressures. Kasim and Fei (2002) conducted two sets of parametric analysis, one set was with core and the other set was without core. The study shows that there is a linear relationship between the downstream flux quantity and maximum seepage velocity within the cross section of the dam.

Although several studies have been carried out, there are still many points to be addressed in seepage analysis. The objective of this paper is to compare the seepage (discharge) calculated by the numerical method (FEM) and analytical solutions for numerically modelled earth dams of different geometric models, to study the effect of mesh, variation of upstream and downstream angle, internal core and its shape, the basement type (pervious or impervious) on the seepage characteristics of earth dam. Analytical methods such as Schaffernak (1917), Casagrande (1937) and Fakhari and Ghanbari (2013) have used to compute the discharge rate where as FEM based software SEEP/W (2007) has used to solve the discharge rate for numerical analysis. The results are compared and the effects of different parameters are reported.

Methodology:

1 Analytical Methods:

Schaffernak (1917) presented an equation for calculating the seepage from the body of a homogenous dam placed on an impervious foundation as follows:

$$q = kl \sin\beta \tan\beta \qquad (1)$$

where,

$$l = \frac{d}{\cos\beta} - \sqrt{\frac{d^2}{\cos^2\beta} - \frac{H^2}{\sin^2\beta}} \qquad (2)$$

Here, β, d and H are the angle of downstream slope, length of drainage path and height of upstream water, respectively (Fig. 1).

Casagrande (1937) proposed equations for evaluating the amount of discharge rate passing through the body of a dam by assuming that the hydraulic slope dz/dx equals to dz/ds as follows:

$$q = kl \sin^2\alpha \qquad (3)$$

where,

$$l = s - \sqrt{s^2 - \frac{h^2}{\sin^2\alpha}} \qquad (4)$$

$$s = \sqrt{d^2 + h^2} \qquad (5)$$

$$d = b - 0.7\Delta \qquad (6)$$

Here, α, h and b are downstream angle, downstream water height and width of core floor, respectively(Fig. 2). Stello (1987) presented a design chart to predict the phreatic line of the dam body and discharge rate that pass through the dams which are located on an impervious foundation. Stello (1987) proposed Eq.(7) to calculate the seepage passing from the body of the dam.

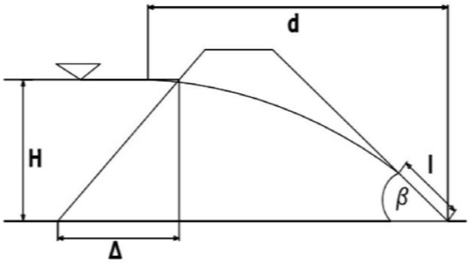


***Figure 1**: Schematic diagram of dam for Schaffernak's (1917) solution.*

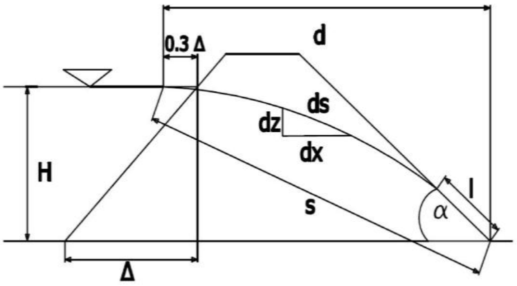


***Figure 2**: Schematic diagram for Casagrande's (1937) solution*

$$q = kmh \qquad (7)$$

In this equation, *m* is calculable for various angles of upstream slope and the *d*/*h* is a ratio in which *h* is the height of upstream water and *d* is calculable from Eq. (6).

Fakhari and Ghanbari (2013) presented equations for estimating the discharge rate through vertical and inclined clay core as follows:

$$q = fkh \qquad (8)$$

$$f = (2.27 - 0.006w - 0.004h - 0.38\tan\alpha) \times H^{(-0.361)} \times \left(\frac{c}{h}\right)^{i} \qquad (9)$$

where, $i = 0.3947\tan\alpha + 0.0015h - 1.3591 \qquad (10)$

and $c = b - 0.7\Delta \qquad (11)$

Here, b and f are the base width and seepage factor, respectively.

2 Numerical Methods:

In this study, numerical analyses have been performed using SEEP/W (2007). Steady state seepage analysis has been conducted. Both the impervious and pervious bases are considered. Models with clay core and without clay core have been analyzed. Factors such as the effect of mesh, clay core shape, upstream and downstream slope angle, the basement type (pervious or impervious) on the seepage characteristics of earth dam have been investigated. Parameters used in this study are depicted in Table 1.Theanalysis conditions to investigate the effect of these factors are described in the following sections:

***Table 1** Parameters used in the study*

Parameters	Values
Crest width (W)	8 m
Dam height (H)	15 m
Water height (h)	12-14m
Up & down stream angle (α and β)	35-45 degree
Mesh shape	Triangles only, Rectangular grid of quads, Quads and Triangles, Triangular

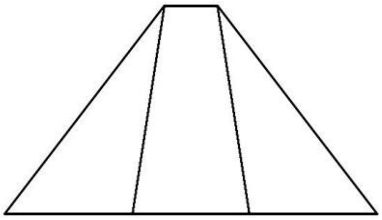
	grid of quads
Hydraulic conductivity (outer soil) , k (m/s)	1x10^{-3} to 1x10^{-9}
Hydraulic conductivity (core), k_{core}(m/s)	1x10^{-6} to 1x10^{-11}

2.1 Effect of mesh shape, size and number:
For this purpose, four mesh shapes were considered. They are: triangles only, rectangular grid of quads, quads and triangles and triangular grid of quads. Numerical models have been analyzed varying the size of mesh, number of mesh for each mesh shape. Hydraulic conductivity is assumed constant for every numerical model.

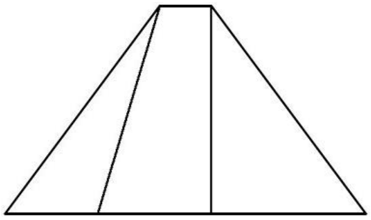
2 .2 Effect of upstream and downstream angle:
For this purpose, three sets of upstream and downstream angles (35, 40, 45 degree) were considered for the dam body. The magnitudes of upstream and downstream angles were same for each model. Crest width, dam height, and hydraulic conductivity of both dam material and the internal clay core for each set of angle were fixed. The analysis is performed for models with clay core and without clay core. Later, it has been analyzed for varying downstream angles.

2.3 Effect of hydraulic conductivity:
For this purpose, numerical models were analyzed in terms of the permeability condition of the base of dam (pervious or impervious). Models are also analyzed considering internal clay core and without internal clay core. At first, models were analyzed considering pervious or impervious base (no internal core) with varying hydraulic conductivity of the dam materials. Later, the models were analyzed with clay core in which the hydraulic conductivity of dam materials was fixed while varying the hydraulic conductivity of internal core.

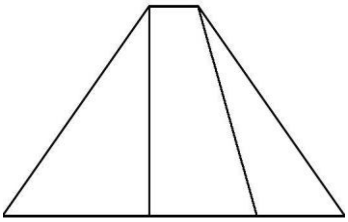
2.4 Effect of the shape of internal clay core:
Numerical analysis for this purpose is carried out by assuming four distinct shapes of the core as shown in Fig. 3. All the parameters for dam are fixed and seepage is measured only varying the core shape and base permeability. Cross sectional area of internal clay core is considered constant for different shapes of internal core so that it has no effect on the seepage measurement.



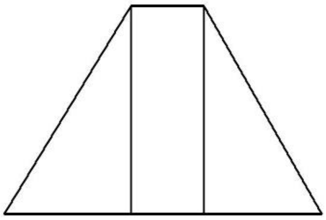
Core Shape-1



Core Shape-2



Core Shape-3



Core Shape-4

***Figure 3**: Shapes of internal core for seepage analysis.*

Results and Discussions:

1 Comparison between Analytical and Numerical results:

The results obtained from the analytical and numerical solution have been presented in Table 2. It is noted that the discharge rate obtained from the numerical analysis is similar to that of the analytical solution by Casagrande (1937) and Stello (1987) compared to Schaffernak (1917) and Fakhari (2013) when same upstream and downstream angle are considered in homogeneous earth dam. Similar conclusion is observed from Table 3 when different upstream and downstream angles are considered.

***Table 2** Comparison between numerical and analytical results for homogeneous dam (Same upstream and downstream angle)*

α or β	Crest width W (m)	Dam Height H (m)	Water Height h (m)	k (m/sec)	Seepage,q (m^3/sec)				
					q Schaffernak	q Casagrande	q Stello	q Fakhari and Ghanbari	q SEEP/W
45	8	15	14	1.00E-06	5.2650E-06	3.5023E-06	4.4800E-06	5.5464E-06	4.0718E-06
	8	15	13	1.00E-06	5.0000E-06	2.9391E-06	4.1600E-06	4.7346E-06	3.4331E-06

	8	15	12	1.00E-06	4.7632E-06	2.4407E-06	3.8400E-06	3.9890E-06	2.8495E-06
40	8	15	14	1.00E-06	4.7475E-06	3.1416E-06	3.5000E-06	4.9385E-06	3.6640E-06
	8	15	13	1.00E-06	4.4868E-06	2.6236E-06	3.2500E-06	4.1769E-06	3.0511E-06
	8	15	12	1.00E-06	4.2567E-06	2.1695E-06	3.0000E-06	3.4857E-06	2.5254E-06
35	8	15	14	1.00E-06	4.2413E-06	2.7852E-06	2.5200E-06	4.3002E-06	3.3285E-06
	8	15	13	1.00E-06	3.9877E-06	2.3151E-06	2.3400E-06	3.6060E-06	2.7563E-06
	8	15	12	1.00E-06	3.7669E-06	1.9067E-06	2.1600E-06	2.9827E-06	2.2819E-06

***Table 3** Comparison between numerical and analytical results for homogeneous dam (Different upstream and downstream angle)*

α	β	Crest width W (m)	Dam Height H (m)	Water Height h (m)	*k* (m/sec)	Seepage,q (m^3/sec)			
						q Schaffernak	q Casagrande	q Fakhari and Ghanbari	q SEEP/W
45	40	8	15	14	1.00E-06	4.7928E-06	3.2503E-06	5.1546E-06	3.7315E-06
	35	8	15	14	1.00E-06	4.3250E-06	2.9873E-06	4.7511E-06	3.4364E-06
	30	8	15	14	1.00E-06	3.8525E-06	2.7078E-06	4.3278E-06	3.0388E-06
	25	8	15	14	1.00E-06	3.3653E-06	2.4052E-06	3.8746E-06	2.6740E-06
40	45	8	15	14	1.00E-06	5.2117E-06	3.3792E-06	5.3330E-06	3.9978E-06
35		8	15	14	1.00E-06	5.1477E-06	3.2393E-06	5.0825E-06	3.9287E-06
30		8	15	14	1.00E-06	5.0680E-06	3.0761E-06	4.7865E-06	3.8534E-06
25		8	15	14	1.00E-06	4.9642E-06	2.8798E-06	4.4300E-06	3.7391E-06

2 Effect of Mesh on Seepage:

Seepage analysis for determining the effect of mesh have been performed by considering four types of mesh shape and varying mesh size. The mesh shapes considered are: triangles only, quads and triangles, rectangular grid of quads and triangular grid of quads. Figs. 4 and 5 show the effect of mesh shape and size on the seepage through the earth dam. It is noted that variation of seepage is dominant up to mesh number of 150 and beyond that, the difference is not significant. It is also noted that smaller the shape size, lower the variation of discharge rate regardless of mesh shape.

3 Effect of Upstream and Downstream Angle on Seepage:

Same upstream and downstream angle

Fig. 6 depicts the effect of the variation of upstream and downstream angles on the discharge rate without any internal core while Fig. 7 depicts the same considering the internal clay core. In case of homogeneous earth dam, the discharge rate decreases with the decrease of both the height of the water head and the upstream and downstream angle. However, Fig. 7 shows that the change of upstream or downstream angle has no influence on the discharge rate when the numerical dam has inter core.

Different upstream and downstream angle

Figs. 8 and 9 state that discharge increases due to increase in upstream and downstream angles in case of dams with internal clay core and without internal core when upstream and downstream angles are not same.

4 Effect of Hydraulic Conductivity on Seepage:

Figs.10 and 11depict the effect of basement type of dam. It is noted that discharge rate is higher for pervious base. From Fig.10, it can be noted that effect of base type (pervious or impervious) on seepage is negligible when core is not used. However, base type (pervious or impervious) affects the seepage for larger values of hydraulic conductivity (k) when internal clay core is used. When k is very small, base type is has no effect of seepage.

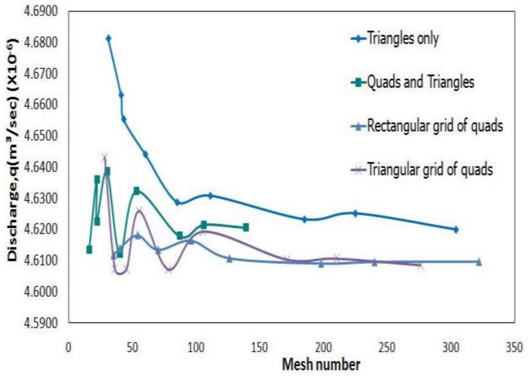


***Figure 4**: Seepage variation due to mesh number*

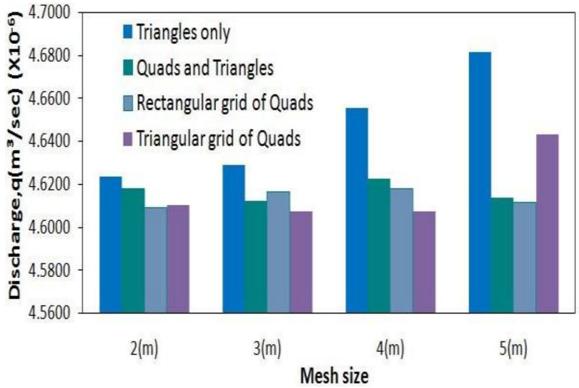


***Figure 5**: Seepage variation for different mesh shape due to mesh size.*

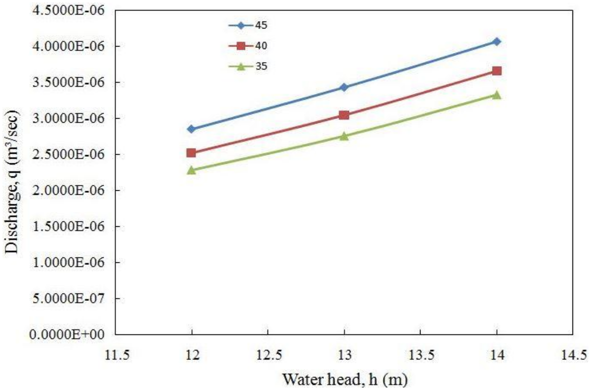


***Figure 6**: Variation of discharge due to variation of upstream and downstream angles without any core*

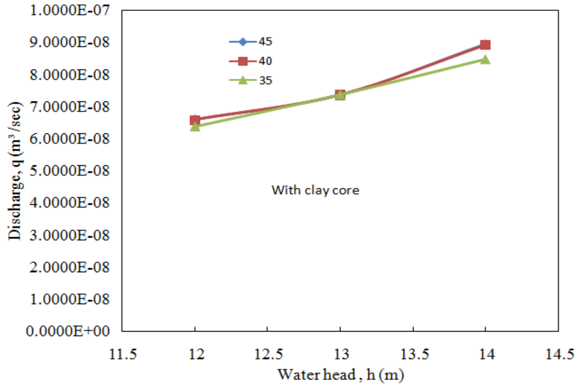


***Figure 7**: Variation of discharge due to variation of upstream and downstream angles with core*

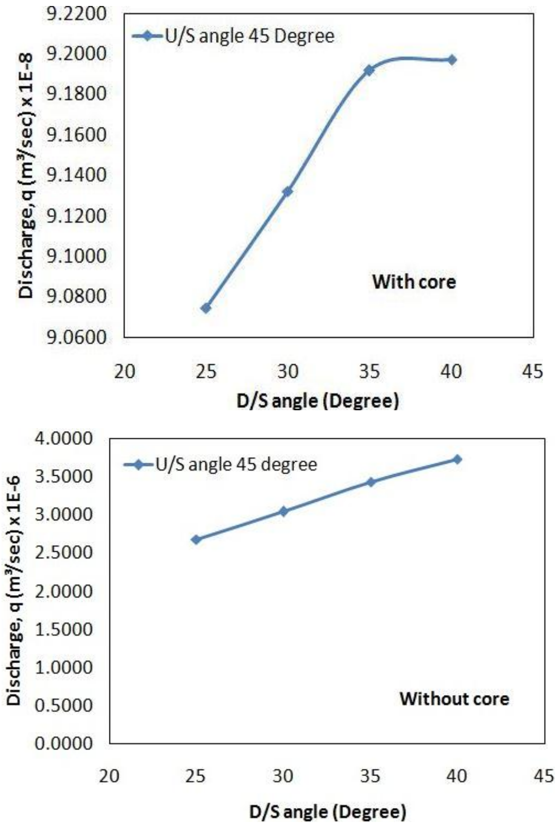


***Figure 8**: Variation of discharge for earth dam with* internal clay core *and without* internal clay *core* for varying *downstream angle*.

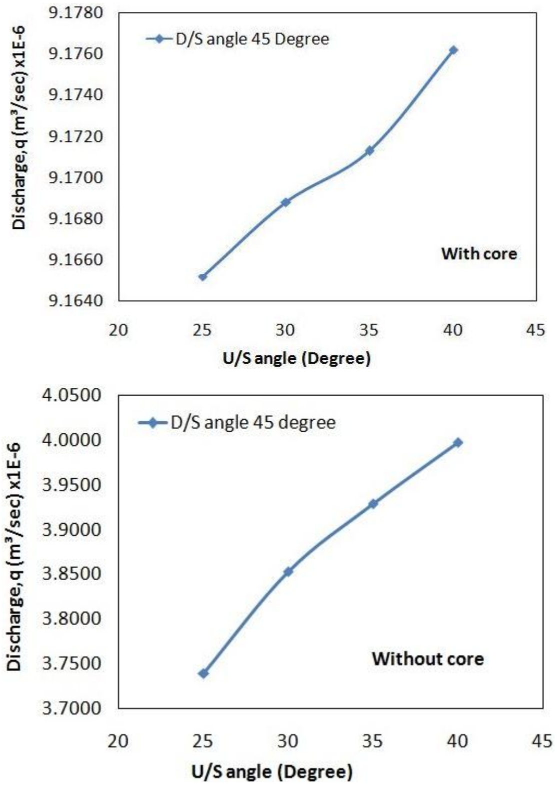


***Figure 9**: Variation of discharge for earth dam with* internal clay core *and without* internal clay *core* for varying upstream angle.

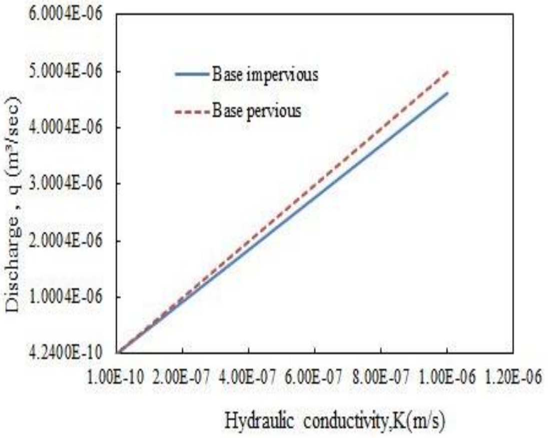


Figure 10: *Effect of hydraulic conductivity without core on seepage for pervious and impervious base on seepage.*

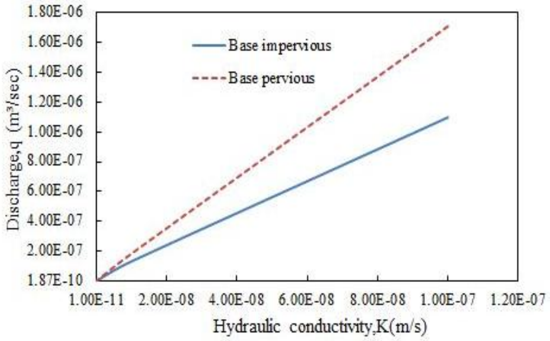


Figure 11*:* *Effect of hydraulic conductivity with core on seepage for pervious and impervious base on seepage.*

5 Effect of Internal Clay Core Shape on Seepage:

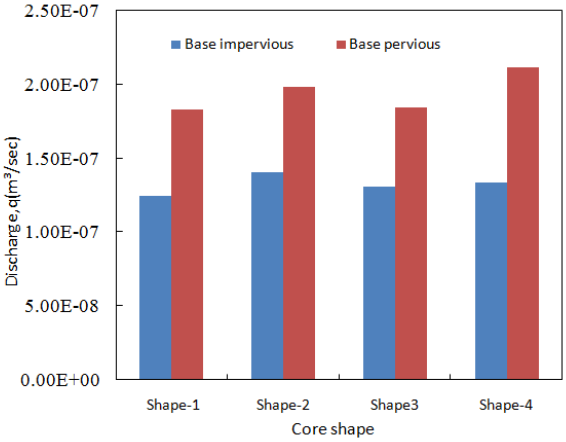


Figure 12*:* *Variation of discharge due to various shapes of internal clay core.*

Fig.12 shows the effect of clay core shape on the seepage of earth dam. It is noted that core shape-1and core shape-3 gives the lowest discharge. In case ofimpervious base, shape-2 and in case of pervious base, casse-4 gives higher discharge. Thus core shape-4 should be avoided in earth dam construction

Conclusions:

In this study, numerical analysis has been performed to investigate the seepage in earth dam under varying factors and conditions such as the effect of mesh, clay core shape, upstream and downstream slope angle, the basement type (pervious or impervious). Numerical results of about 100 models are presented. Some of the important points of the study are as follows:

1. Seepage varies up to mesh number 150; however, seepage remains almost constant for mesh number beyond 150.
2. Mesh shape and mesh size has negligible effect on seepage.
3. Noticeable reduction of the discharge rate is observed with the addition of clay core in the model. It should be noted that upstream and downstream angle has no effect on discharge rate when internal clay core is used but the discharge rate increases due to increase in upstream and downstream angle without internal clay core.
4. Seepage rate are higher for pervious base. When internal core is not provided thedifference of seepage between pervious and impervious base is less. The difference of seepage rate is higher between pervious and pervious base when internal clay core is provided.
5. Core shape has significant effect on seepage. All the shapes considered in this study give higher discharge in case of pervious base than impervious base. The trapezoidal shape (shape-1) gives least discharge both for pervious and impervious base compared to other shapes. Thus trapezoidal shape of core is preferable than rectangular shape.

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