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Emperical and Numerical Solution Of Seepage Problems Underneath Hydraulic Structures

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ABSTRACT

Hydraulic structures are structures submerged or partially submerged in water, they're used to retain or divert natural water flow. Any hydraulic structure that retains water is faced with seepage problems as the water seeks the path with the least resistance through or under the hydraulic structure. If the water carries materials as it flows or exerts high pressure on the floor of the structure, it will cause failures such as piping and cracks and there are many ways to prevent that, including cutoffs. In this paper, seepage is analyzed for different cases by using the empirical method (Khosla's theory) and the numerical method by using computer software (SEEP/W). The results had some slight differences between the two methods as a result of not taking into account the effect of soil characteristics of the empirical method. However, the water pressure heads underneath the impervious floor that calculated by the numerical method were greater.

1. Introduction

Optimum use of water nowadays cannot be overemphasized. Hydraulic structures are a specific type of engineering structures designed and executed in order to utilize it to control water and ensure the aforementioned objective. The hydraulic structures represent an important part of any flow network. Examples of such structures are dams, regulators, weirs, etc. the basic aim of these structures is to control the flow discharge and water levels. The foundation of any hydraulic structure should be given the greatest importance in analysis and design as compared with other parts of the structure because failure in the foundation would destroy the whole structure. One of the most important problems that cause damage to hydraulic structures is seeping under the foundations, which occurs due to the difference in water level between the upstream and downstream sides of the structures. The water seeping underneath the hydraulic structure endangers the stability of the structure and may cause failure. Water seeping under the base of a hydraulic structure starts from the upstream side and tries to emerge at the downstream end of the impervious floor. If the exit gradient is greater than the critical value of the foundation, a phenomenon called piping may occur due to progressive washing and removal of the fines of the subsoil (1). Moreover, the uplift

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force which occurs as a result of water seeping below the structure exerts an uplift pressure on the floor of the structure. If this pressure is not counterbalanced by the weight of the floor, the structure may fail by rupture of a part of the floor. Seepage problems are of primary importance for stability analysis and in foundation design and construction of hydraulic structures; these problems mainly include piping and uplift pressure. It is best for these structures and their foundations to be designed to withstand such pressures. However, in many cases, seepage problems are bound to occur at some point which is why it has been getting significant attention in the last decade.

In order to avoid these problems, various methods of seepage and percolation control means can be used to satisfy the requirements for preventing uneconomical loss of water depending on the nature of the foundation as regards stability for seepage forces. The ordinary devices available for use are (2):

1. Upstream blanket.

2. Upstream and/or downstream cutoffs (sheet piles).

3. Subsurface drain on the downstream side.

4. Filter trench on the downstream side.

5. Weep holes, or pressure relief wells on the downstream side.

The problem of seepage underneath hydraulic structures has been studied widely and in various ways by many researchers, due to the importance of this issue and its impact on the safety of the facilities and the lives of people. Some of these studies can be cited here as examples.

Karim and Hisham in 2013 (3) inspected the seepage analysis through and underneath the hydraulic structure simultaneously, without dividing and analyzing each part on its own. They compared the results obtained from finite volume method and finite element method and the results were close. Furthermore, they studied the effect of the heterogeneity and homogeneity of foundation, and also they studied the effect of inclination and position of cut-off in upstream and downstream on the uplift pressure and exit gradient at downstream.

Aqeel et al in 2012 (4) studied problems of the Diyala weir by using the two dimensional finite element models in GeoSlope to analyze the effect of seepage of water underneath Diyala weir foundation. They calculated the thickness of the floor and stability against uplift pressure and the safety against piping and both calculations gave results that indicated that the existing stability and safety is inadequate.

Khassaf et al in 2008 (5) utilized the finite element in Seep/w to analyze the seepage under the Diyala weir foundation. Two dimensional model of quadrilateral finite element was used to solve the problem.They studied the effect of removing one of the 3 sheet piles rows and calculated the amount of seepage, uplift pressure and exit gradient for this case. They discovered that the foundation problems are caused by the corrosion of the upstream sheet piles.

Raad and Abdulghani in 2012 (6) studied the efficiency and performance of Mosul Dam with respect of the seepage depended on the dam field observations of years 2004, 2003 and 1990. The results concluded that the dam embankments being a good efficiency with respect the seepage.

Abdulghani et al in 2006 (7) analyzed seepage through porous media below hydraulic structures with blanket, Cut-off, or filter trench as seepage control devices by using the finite-element method. The effect of length and location of the control devices is investigated. The formulated optimization model is applied to a hypothetical case study.

Asmaa in 2016 (8) studied the effect of using intermediate sheet pile under the apron of hydraulic structure besides the upstream and downstream piles rest on non-homogeneous soil layer to show how it affects the uplift pressure, exit gradient and seepage discharge at toe of hydraulic structure by using computer program SEEP/W.

Mohammed in 2018 (9) studied the effect of mutual interference piles on seepage phenomenon by using finite elements program ANSYS. The results were verified with practical results which given a good correlation. It was found that the use of the pile in the upstream reduced the uplift pressures by 8.36%, and the pile in the downstream increased it by 11.66%, the flow rate reduced by 66.8% and exit gradient of the hydraulic structures reduced by 28.28%.

Kheiri et al in 2020 (10) examined the effects of the cutoff wall and the horizontal drain on the flow discharge under the embankment dams. The finite element program of SEEP/W was applied for modeling embankment dam. The results of numerical modeling of the embankment dam were compared with the results of physical modeling demonstrated the acceptable accuracy of the numerical method in the flow evaluation.

Reviewing literature indicates that the water seepage under the impervious floor of a hydraulic structure needs further studies. This study mainly aims to compare the results of water pressure obtained from the empirical and numerical methods and then determine the safe thickness of the hydraulic structure's impervious floor.

2. Methodology:

The term seepage often is used to describe flow problems in which the dominant driving energy is gravity, such as a case in which seepage losses occur from a reservoir to a downstream exit point. In other situations such as consolidation, the primary driving energy may be associated with the creation of excess pore-water pressures as a result of external loading. However, both of these situations can all be described by a common set of mathematical equations describing the water movement. As a result, the formulation used to analyze seepage problems can also be used to analyze the dissipation of excess pore-water pressures resulting from changes in stress conditions. Simulating the flow of water through soil with a numerical model can be very complex. Natural soil deposits are generally highly heterogeneous and non-isotropic. In addition, boundary conditions often change with time and cannot always be defined with certainty at the beginning of an analysis. In some cases the correct boundary conditions themselves are part of the outcome from the solution. (11)

Furthermore, when soil becomes unsaturated, the coefficient of permeability or hydraulic conductivity becomes a function of the negative pore-water pressure in the soil. Since the pore-water pressure is related to the primary unknown (total head) and must be computed, iterative numerical techniques are required to compute the appropriate combination of pore-water pressure and the material property. This is referred to as a non-linear problem. These complexities make it necessary to use some form of numerical analysis to analyze seepage problems for all but the simplest cases.

The flow chart in **Figure 1** demonstrates the methodology used in this paper.

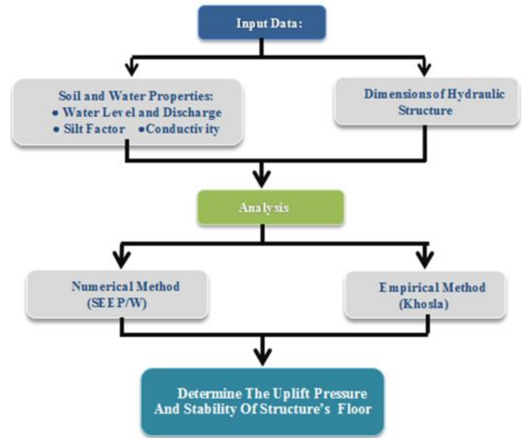

Figure 1. Flow Chart Of Methodology

3. Theoretical consideration

3.1 Empirical Method (Khosla's Theory):

Khosla's method is considered to be the most complex and accurate method to determine the uplift pres-sure underneath the hydraulic structure. In his method three key points are specified for each cut-off, E, D and C (see **Figure 2**).

The following formulas are used to determine the percentage of uplift pressure at key points for floor with an intermediate piles as shown in **Figure 3** :(12)

$$\%\emptyset_E = 0.318\left(\frac{n_1 - n_2 - 2}{n_1 + n_2}\right) \qquad [1]$$

$$\%\emptyset_D = 0.318\left(\frac{n_1 - n_2}{n_1 + n_2}\right) \qquad [2]$$

$$\%\emptyset_C = 0.318\left(\frac{n_1 - n_2 + 2}{n_1 + n_2}\right) \qquad [3]$$

Where n1 and n2 are computed by:

$$n_1 = \sqrt{1 + (\frac{b_1}{d})^2} \qquad [4] \quad ,$$

$$n_2 = \sqrt{1 + (\frac{b_2}{d})^2} \qquad [5]$$

And hence for floor with sheet pile at the up-stream end, The following formulas are used to determine the percentage of uplift pressure at key points as shown in **Figure 3**:(12)

And hence for floor with sheet pile at the down-stream end , The following formulas are used to determine the percent of uplift pressure at key points as shown in **Figure 4** (12, 13).

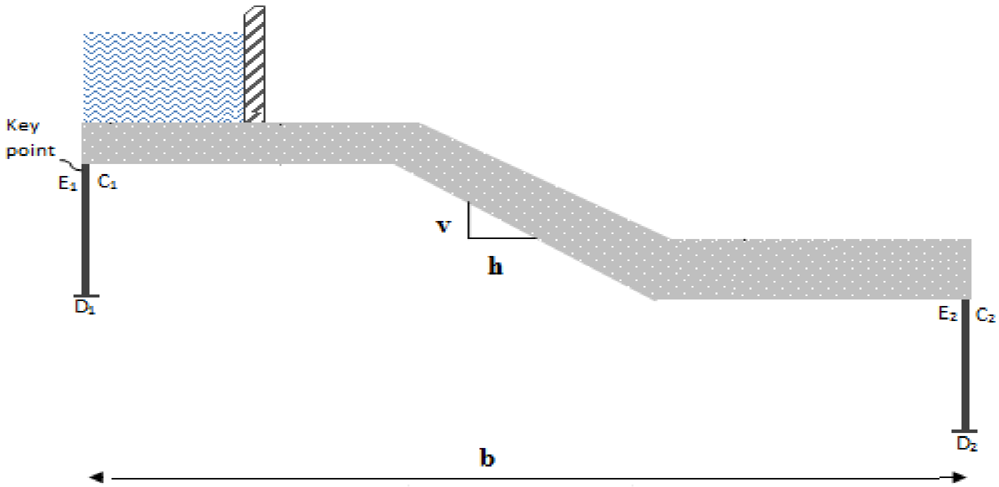

Figure 2 The three key points E, D and C for each cut-off underneath a hydraulic structure

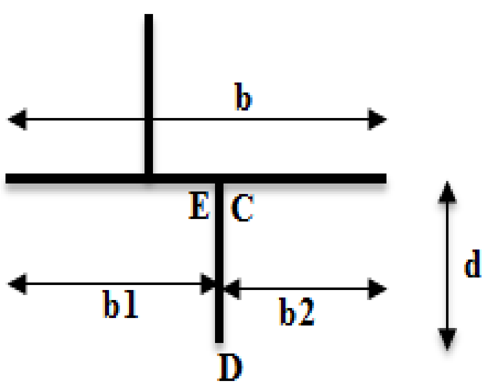

Figure 3 The three key points E, D and C for intermediate pile underneath a hydraulic structure

$$\%\emptyset_{C1} = \frac{100}{\pi}\cos^{-1}\left(\frac{2-\lambda}{\lambda}\right) = 100 - \emptyset_E \quad [6]$$

$$\%\emptyset_{D1} = \frac{100}{\pi}\cos^{-1}\left(\frac{1-\lambda}{\lambda}\right) = 100 - \emptyset_D \quad [7]$$

Where, $\lambda = \frac{1+\sqrt{1+\alpha^2}}{2}$, $\quad \alpha = \frac{b}{d}$

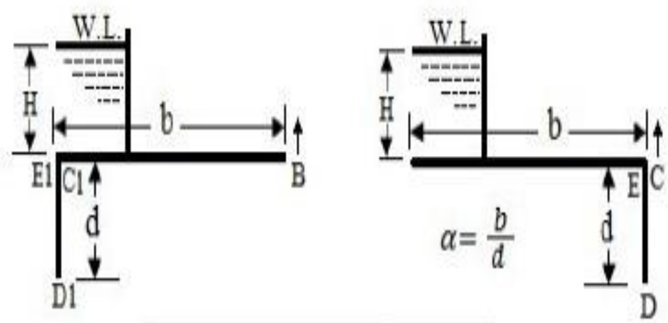

Figure 4 The three key points E, D and C for end piles underneath a hydraulic structure

$$\%\emptyset_E = \frac{100}{\pi}\cos^{-1}\left(\frac{\lambda-2}{\lambda}\right) \quad [8]$$

$$\%\emptyset_D = \frac{100}{\pi}\cos^{-1}\left(\frac{\lambda-1}{\lambda}\right) \quad [9]$$

However, these values of percent of uplift pressure at key points are not corrected and need to make the following corrections:

a) Correction for interference of piles.

b) Correction for the thickness of floor.

c) Correction for the slope of the floor.

Khosla and his associates took into account the flow pattern below the impermeable base of hydraulic structure to calculate uplift pressure and exit gradient.

To calculate the exit gradient GE for floor of length b with vertical D/S sheet pile of depth d can be used the following formula (12):

$$G_E = \frac{H}{d} \cdot \left(\frac{1}{\pi\sqrt{\lambda}}\right) \quad [10]$$

The thickness of floor can also be obtained from the residual head , thus:

$$t = \frac{h}{G_f - 1} \qquad (11)$$

Where Gf is the specific gravity of the floor material and the value of (h) is the residual head.

In general, for concrete material the specific gravity Gf is 2.5. Therefore, we can re-write equation 11 as the following(13):

$$t = \frac{2}{3} h \qquad (12)$$

Equation 12 is used to calculate the thickness of impervious floor in this paper for analysis and safety checking purposes.

3.2 Numerical Method SEEP/W:

SEEP/W is a powerful finite element software product for modeling groundwater flow in porous media. SEEP/W can model simple saturated steady-state problems or sophisticated saturated / unsaturated transient analyses with atmospheric coupling at the ground surface.

While the software is an extremely powerful calculator, obtaining useful and meaningful results from this use-ful tool depends on the guidance provided by the user. It is the users' understanding of the input and their ability to interpret the results that make it such a powerful tool (11).

In summary, the software does not do the modeling, the user does the modeling. The software only pro-vides the ability to do highly complex computations that are not otherwise humanly possible. In a similar manner, modern day spreadsheet software programs can be immensely powerful as well, but obtaining useful results from a spreadsheet depends on the user. It is the user's ability to guide the analysis process that makes it a powerful tool. The spreadsheet can do all the mathematics, but it is the user's ability to take advantage of the computing capability that leads to something meaningful and useful. The same is true with finite element analysis software such as SEEP/W. Numerical modeling is a skill that is acquired with time and experience. Simply acquiring a software product does not immediately make a person a proficient modeler. Time and practice are required to understand the techniques involved and learn how to interpret the results. So, SEEP/W is a numerical model that can mathematically simulate the real physical process of water flowing through a particulate medium (11).

4. Results And Discussion

In order to compare between the empirical and numerical methods; a theoretical example (13) shown in **Figure 5** was solved by both methods.

For the empirical solution of the case solved. Percentages of uplift pressure on key points must be corrected due to effect of piles (Corr. 1), effect of floor thickness (Corr. 2) and effect of floor slope (Corr. 3). Uplift pressure and residual water pressure to the key points were calculated as shown in **Table 1**. The residual water pressure is the difference between water head (above the point) and uplift pressure head at the point.

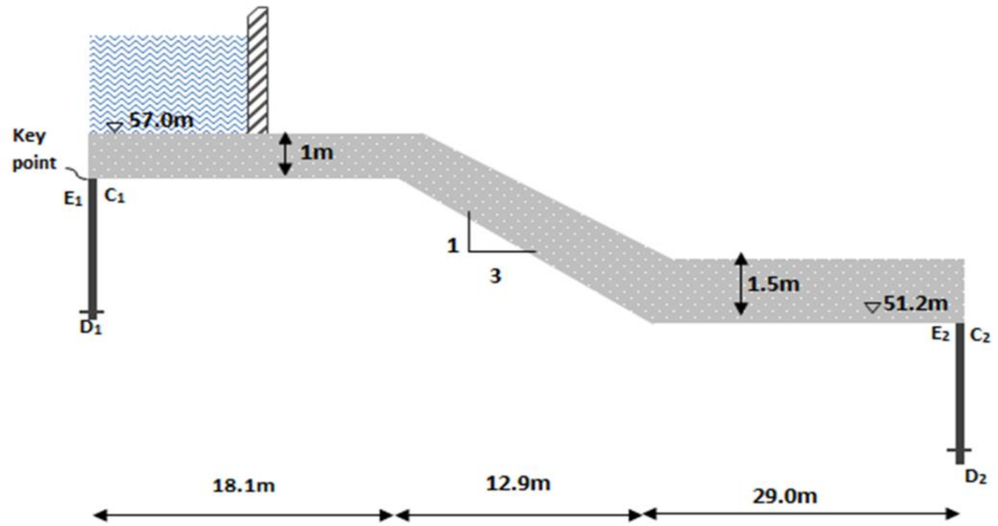

Figure 5 The theoretical problem was used in this paper.(Q = 1980m^3/sec, water way = 85m, High flood level=61.7m ,U/S .(water level =60.6.m2, D/S High flood level = 61.7m, pond level = 60.6m, safe exit gradient = 1/6, silt factor (f)=1

Table 1. Results From Empirical Solution For Key Points On Cut Off In Upstream And Downstream

Cutoff	Key points	Percentage of uplift pressure	Correction			Percentage of uplift pressure correction	Uplift pressure (m)	Residual Water pressure head (m)
			Corr.1	Corr.2	Corr.3			
Upstream	E1	100%	-	-	-	100%	7.9	4.3
	D1	78%	-	-	-	78%	6.162	4.94
	C1	68%	2.35%	1.33%	-	71.68%	5,663	2.063
Downstream	E2	32%	-0.42%	-2%	-	29.58%	2.33	2.33
	D2	22%	-	-	-	22%	1.738	1.738
	C2	0	-	-	-	0	0	0

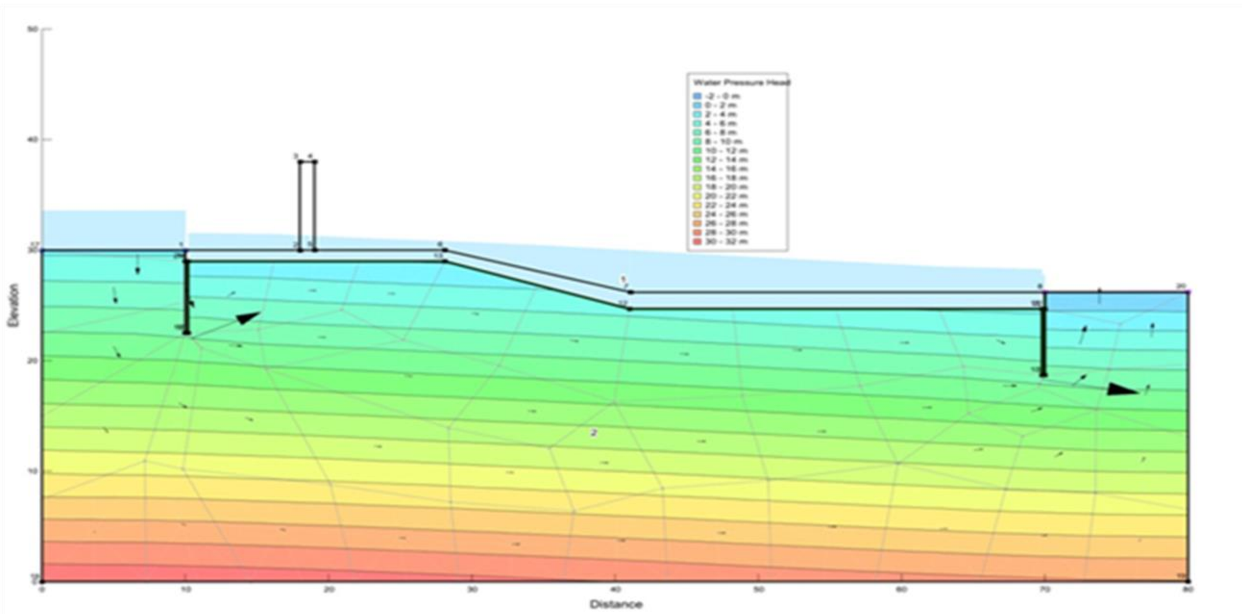

Figure 6 The water pressure head distribution underneath the structure

For the numerical solution of the case solved above, SEEP/W was used to analyze it. By using the bounda-ry conditions of upper head of 33.6m, lower head of 26.2m. The material is defined as silt with conductivity of 7*10-8 m/s. The water pressure head distribution underneath the hydraulic struc-ture is shown in **Figure 6.**

Table 2 illustrates the pressure head for the key points on the cutoff while **Table 3** shows the results of residual water pressure head on key points in both methods (empirical and numerical methods) and the calculated values of floor thickness.

The base of the impervious floor is subjected to uplift pressures as the water seeps through below it. The uplift upstream of the hydraulic structure is balanced by the weight of water standing above the floor in the pond. Whereas on the downstream side there may not be any such balancing water weight (14). Therefore, the thickness of impervious floor in downstream is greater than that in upstream. The residual pressure head re-sults of two points (C1 and E2) were taken to calculate the thickness of im-pervious floor in upstream and downstream, respec-tively by using equation 12 (see **Table3**).

Table 2. Results From Software For Key Points On Cut Off In Upstream And Downstream

Cut-off	Node	Water pressure (kPa)	Water total head (m)	Water pressure head (m)
Upstream	11 (E1)	43.257353	33.410865	4.410865
	10 (D1)	94.481129	32.13405	9.6340501
	12 (C1)	25.244152	31.564095	2.5740952
Downstream	60 (E2)	35.457408	28.28552	3.6155203
	59 (D2)	90.059059	27.873141	9.1831405
	61 (C2)	17.410904	26.445355	1.7753547

Table 3 The Results of Water Pressure Head (m) of key points in both methods

	Key Points	Residual Water Pressure Head (m)		Thickness of Floor (m)		
		Khosla's Theory	SEEP/w	Khosla's Theory	SEEP/w	In example
U/S	E1	4.3	4.41			
	D1	4.94	9.63			1
	C1	2.063	2.57	1.38	1.71	
D/S	E2	2.33	3.61	1.55	2.41	1.5
	D2	1.738	9.18			
	C2	0	1.77			

In both methods, the result values of impervious floor thickness were more than the thickness values of the problem (**Figure 5**). On the other hand, the values of floor thickness that were calculated by SEEP/W were the thickest due to uplift pressures in the key points that calculated.

5. Conclusion and recommendations

Integrating numerical solutions for analyzing seepage problems and case studies help in developing an under-standing of the water's behavior underneath the structures. The software used in this project (SEEP/w) is a fairly easy to use and fast tool, as users utilize the features of the program they get a better understanding of its process. In addition to that, different information can be obtained in one case, at any point under the struc-ture. However, that is not to say that the empirical methods are not as essential, they are the base for under-standing seepage analysis.

Though some methods are outdated and basic others, like Khosla's theory, are con-sidered to be the most accurate calculations.

The results from both methods vary slightly in some key points and significantly in others because of the em-pirical method (Khosla's theory) depends mainly on the difference between the pond and downstream floor levels (7.9m). Also, it depends on the length and thickness of the impervious floor (the thickness of the down-stream floor is increased to withstand the uplift pressure). However, in the numerical solution (SEEP/W) while it too depends on the factors mentioned above it also relies on the soil condition and the head difference is between the pond level and upstream floor elevation (3.6m).The difference is mostly noticeable in the points that are far from the floor of the structure (D1 and D2) because the soil has a bigger effect on it.

The water pressure head at the downstream cutoff (sheet pile) increases in the software solution at points E2 and D2 because the cutoff is blocking the water's path, making it exert higher pressure on these points, that is not taken into consideration in the em-pirical method. Regarding the thickness of the imper-vious floor, it is depending on the value of residual head pressure above the point to be calculated. Usually the value of intersection point between the pile and the floor (E2) is taken to calculate the floor thickness in the downstream (with presence a sheet pile).

This paper had limited resources to real-life cases and even virtual ones, and it was mainly solved for water head pressure and floor thickness by using Khosla's theory and SEEP/W. However, other methods could be used to estimate these parameters. For instance sketching a flow net to compute pressure at random points in-stead of specific key-points, which gives more results to contrast with software ones.

Nomenclature

%$\emptyset$ The percent of uplift pressureat key point.

GE Exit gradiant

d Depth of pile.

b Horizontal length of flow.

H The difference between water level in u/s & d/s.

t Thickness of impervious floor.

h Uplift pressure.

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