EVALAUTE THE BEST INCLINATION ANGLE OF CUTOFF BENEATH HYDRAULIC STRUCTURES

A. M. Elmolla[1], W. A. Abd Elgalil[2], M. A. Dardeer[3] and Adel. A. Elshimy[4]

[1]Prof. of Irrigation and Hydraulics, Faculty of Engineering, Al-Azhar University, Egypt
[2]Ass. Prof. of Irrigation and Hydraulics, Faculty of Engineering, Al-Azhar University, Egypt
[3]Lecturer of Irrigation and Hydraulics, Faculty of Engineering, Al-Azhar University, Egypt
[4]TA of Irrigation and Hydraulics, Faculty of Engineering, Al-Azhar University, Egypt

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ABSTRACT: In terms of the importance of hydraulic structures, this research was started with the impartial of avoiding traditional solutions by implementing vertical cutoffs for the purpose of profiting of its depth and keeping it away of the phreatic line in order to dissipate the energy in the water below the apron and to reduce the potential energy in the water. In this research work, a 2d finite element model (GMS – SEEP2D) is used. In order to achieve the research objectives, a numerical work was executed where the different contributing parameters were varied and investigated (i.e. Seven (7) models were investigated in order to cover the various aspects of the problem under consideration). Measurements were undertaken and documented. These measurements were analyzed, plotted on graphs, presented and discussed. Finally, an optimum configuration was reached and recommended.

KEY WORDS:

Cutoff, Apron, Energy Dissipation, and creep length

1. INTRODUCTION

Seepage under the aprons of heading-up structures causes many problems like piping and excessive uplift pressure that can threaten the stability of the structures. Seepage can't be totally prevented but many seepage control methods are suggested to safeguard structures against the threats of seepage. Adding horizontal length to the apron, using sheet piles or using a drainage blanket downstream the structure's apron are among those methods.

In terms of the importance of reducing the cost of maintenance of their aprons, this study was initiated with the objective of introducing cutoffs to aprons, in an inventive way, to obtain economic hydraulic structures by reducing the seepage.

The effect of sheet pile has been studied in many previous researches using the electric analogue method [ElSalawy, ElMolla and Bakry, 1997; ElSalawy and ElMolla, 2000; Mobasher, 2005; El Tahan, Shafik and ElMolla, 2012]. Other studies used finite element method to investigate seepage under the aprons of heading up structures provided with a single sheet pile [El-Molla, 2001; Hassan, 2004; Obead, 2013]. SEEP2D is a finite element program that has been applied by many researches to study seepage and has proved to be an efficient tool for seepage analysis [El Molla, 2001; Ozkan, 2003; Noori and Ismaeel, 2011; El Molla, 2012; El Molla, 2014; M. A. ElMolla, 2015 and others].

At the present study, investigation of the effect of inclined cutoffs on dissipating the energy of the creep line under the hydraulic structure is founded on one soil layer. A (7) models are conducted and analyzed for evaluate the best Inclinations angle of cutoff beneath hydraulic structures. A 2D finite element model (GMS- SEEP2D) is used.

In order to achieve the research objectives, a methodology was planned, according to which a numerical work was executed where the different contributing parameters were varied and investigated. Measurements were undertaken and documented. These measurements were analyzed, plotted on graphs, presented and discussed. Finally, an optimum configuration was reached; conclusions were deduced and recommendations, for future research were provided.

This paper presents the above under the following headlines:

- Reviewing the literature
- Executing a theoretical study
- Undertaking numerical investigations
- The results
- Conclusions and recommendations

2. REVIEWING THE LITERATURE

Many researchers are occupied in investigating the required length to ensure the safety of hydraulic structures apron. For example:

Bligh (1910) and Soliman, M.N. (1979) assumed that the hydraulic slope, (or gradient), is constant throughout the length ABCD, figure (1). The hydraulic gradient diagram is represented by a triangle with base length (L) which is equal to the length of ABCD. This is called "Length of Creep", which is supposed to be the path of percolation (L_w) of water. The value of the weighted creep length is calculated as:

$$L_W = L_{hz} + L_V = C_B \times H \quad \textbf{(1)}$$

Where:

L_{hz} Sum of horizontal creep lengths

L_V : Sum of vertical creep lengths

C_B : Bligh's coefficient

H : Piezometic head

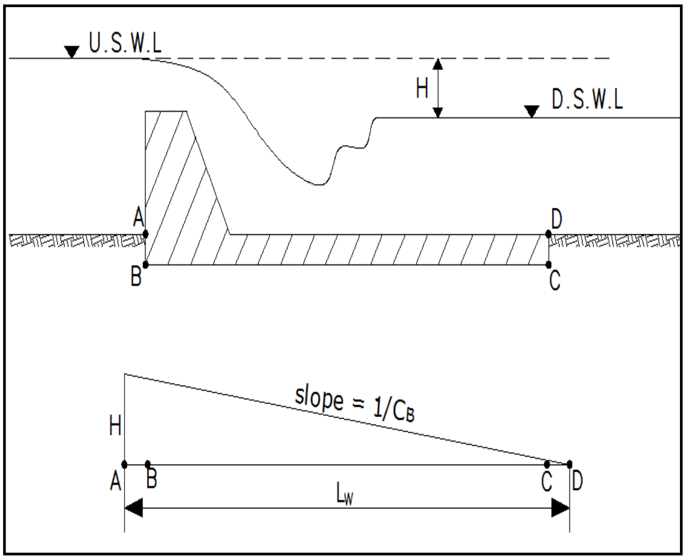

Figure (1) Creep line and Hydraulic Gradient Diagram

Lane (1932) and Soliman (1979) introduced the concept of the line of the least resistance, which the water flow may follow. Lane considered "more weight" for creep along vertical and steeply sloping surfaces, for the following reasons:

- Intimate contact between flat surfaces and soil is not always secured, thus accumulation of streamlines along line of creep is more likely to occur resulting in high velocity, and probable failure.
- Underneath flat aprons, soil may settle locally forming voids, a phenomenon often described as (roofing action). This is dangerous with respect to piping.
- Safety against piping depends mainly on vertical elements of foundation.

Lane developed the a theory where he related L_{hz} (sum of horizontal contacts and all sloping contacts whose angle with the horizontal is less than 45) to L_V (sum of vertical contacts and all sloping contacts whose angle with the horizontal is more than 45) by the following equation:

L_w* (weighted creep length) is equal to:

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$$L_W{}^* = \frac{L_{hz}}{3} + L_V \quad \textbf{(2)}$$

To ensure safety against undermining, L_w* should be as follows:

$$L_W{}^* = C_L.H \quad \textbf{(3)}$$

Where:

CL : An empirical coefficient depending on type of soil

El-Salawy, El-Molla and Bakry (1997) used an electrolytic tank to investigate the effect of both the front and rear faces (upstream and downstream) of the cutoffs on the hydraulic gradient of the creep line in contact with them. Their investigation assisted in the estimation of the actual length of the creep beneath the floor of the hydraulic structures. They concluded that the total effect of cutoff under aprons of hydraulic structures on the creep line depends on its position. As a result, weighted value of the cutoff faces should be used to estimate the whole length of the creep line in case of using either Bligh's or Lane's formulae.

EL- Salawy and El-Molla (2000) used an electrolyte tank to investigate models of aprons of hydraulic structures provided with cutoffs beneath them. The efficiencies of faces, front and/or rear, of these cutoffs on affecting the hydraulic gradient beneath the models of aprons are investigated at various positions for each individual model.

El-Molla (2001) used a computer program called SEEP-2D to investigate the flow pattern for 25 models representing aprons of hydraulic structures provided with a single cutoff of different depths and located at various positions with respect to the horizontal length of the apron.

Mobasher (2005) used an electrolytic tank to investigate models of aprons of irrigation structures provided with cutoffs. He investigated the role of the two faces of a single cutoff under an apron of a control structure, on modifying the hydraulic gradient under which seeping water is motivated.

El Tahan, El-Molla (2013) an electrical analogue model was used to investigate the effect of the depth of the upstream and downstream cutoff D_1 and D_2 respectively when the upstream cutoff is at the start of the apron and the downstream cut off is at the end of the apron on the uplift forces along the hydraulic structure and the rear and front faces head drop of both upstream and downstream cutoff.

Adel Elsheemy (2015) used an electric analogue to study the effect of inclination of cutoffs on the total net potential and horizontal creep length. 225 models were investigated in order to cover the various aspects of the problem under consideration.

3. EXECUTING A THEORETICAL STUDY

In this research, a theoretical study was executed. Models representing apron of horizontal length (Lhz) were founded on pervious isotropic soil of thickness (T). The actual percolation length for every model was investigated under the effect of the applied net potential head (H). The apron provided with cutoff depth (D) located at various positions (X) with respect to the required horizontal length with various angles (θ) in front and rear direction, figure (2).

The actual percolation length for every model is investigated under the effect of the applied net potential head (H).

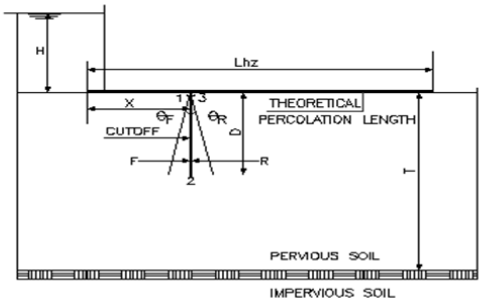

Figure (2) Definition Sketch

3. a. DIMENSIONAL ANALYSIS

During the theoretical study, a dimensional analysis was achieved, as follows:

$$\Phi(H, T, D, L_{hz}, F, R, X, K, \rho, g, \theta_F, \theta_R) = 0 \qquad (4)$$

Where:

g = gravitational Acceleration

ρ = density of seeping water

K = permeability coefficient through the homogeneous stratum of thickness (T)

Equation (4) is supposed include the entire variable involved in the problem of seepage under an apron under a given head (H) provided with a single cutoff in a homogeneous stratum of soil with (K) permeability and (T) thickness.

3. b. DIMENSIONLESS RELATIONSHIP

By applying Buckingham Π- theorem, taking X, g and ρ as repeated variables, the relation could be written as:

$$\Phi\left(\frac{X}{F}, \frac{X}{R}, \frac{X}{D}, \frac{X}{T}, \frac{X}{L_{hz}}, \frac{H}{L_{hz}}, \frac{Xg}{K^2}, \theta_F, \theta_R\right) = 0 \qquad (5)$$

The eight dimensionless terms in (5) were reduced to six terms. By combining both the first and second terms, the third and fourth terms:

$$\Phi\left(\frac{F}{R}, \frac{D}{T}, \frac{X}{L_{hz}}, \frac{H}{L_{hz}}, \frac{Xg}{K^2}, \theta_F, \theta_R\right) = 0 \qquad (6)$$

For the homogeneous soil with known permeability (K) and if (X) is constant, the fifth term reduces to a constant, equation (6) so; any variable has a function as follows:

$$\Phi\left(\frac{F}{R}, \frac{D}{T}, \frac{X}{L_{hz}}, \frac{H}{L_{hz}}, \theta_F, \theta_R\right) = 0 \qquad (7)$$

4. UNDERTAKING NUMERICAL INVESTIGATION

A numerical study was carried out. This section presents the numerical apparatus, numerical program and undertaken measurements, as follows:

4. a. DESCRIPTION OF THE SEEP2D MODEL

SEEP2D is a 2D finite element (steady state) flow model. The two dimensions are the horizontal and vertical dimension (i.e., vertical profile). The SEEP2D software was developed by the United States Army Engineer Waterways Experiment Station to model a variety of problems involving seepage. The governing equation used in the SEEP2D models is the Laplace equation. Transient or time varying problems cannot be modeled using it. SEEP2D allows for different hydraulic conductivities along the major and minor axes (anisotropic conditions) to be defined [SEEP2D Primer, 1998 and El Molla, 2015].

Post-processing includes contouring of the total head (equipotential lines), drawing flow vectors, and computing flow potential values at the nodes. These values can be used to plot flow lines together with the equipotential lines (i.e., flow nets). The phreatic surface can also be displayed [SEEP2D Primer, 1998 and El Molla, 2015].

4. b. MODELING PROCEDURE

The steps/tasks used for each run of the model used in this study are as follows:

1. Choosing the model's dimensions for the run.
2. Drawing the problem (model) on AutoCAD.
3. Choosing the best cell size for the mesh and then mesh generation.
4. Setting boundary conditions.
5. SEEP2D execution.
6. Post-processing of the output.

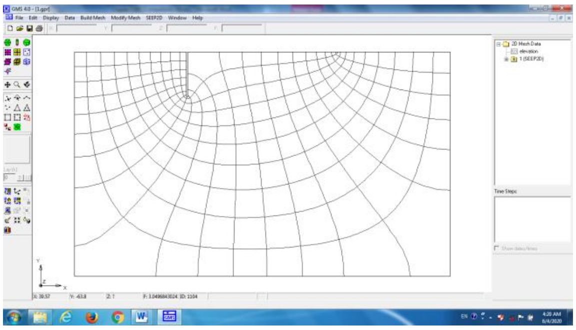

Figure (3) Photo for SEEP2D program setup.

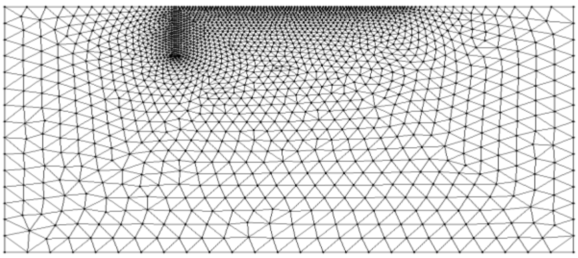

Figure (4): Sample of SEEP2D mesh, cell size 0.5m at cutoff and 4 m otherwise.

4. c. NUMERICAL SIMULATION METHOD

A Numerical program was planned to investigate a depth (D) = 20 m. A 60 m deep heterogeneous soil with a depth ratio (D/T) =0.33, is selected. The length of the apron (L_{hz}) was 40 m. The position of the cutoff is fitted at start point of the apron. The chosen head (H) is 6.0 m.

Seven (7) models are investigated in order to cover the various aspects of the problem under consideration. The potential head is 6.0 m.

The parameters are written in dimensionless form together with their considered range as follows:

- The ratio of cutoff depth to the thickness of the pervious layer (D/T) equal (0.33).
- The ratio of horizontal length of the apron to the thickness of the pervious layer (D/T) equal (0.67).
- The ratio of potential head to the thickness of the pervious layer (H/T) equal (0.1).

5. THE RESULTS

Seven (7) models were executed to five (5) different angles (i.e. 0o, +15o, +30o, +45o, -15o,-30o and -45o) the cutoff fitted at start point of the apron. Measurements were undertaken observations were recognized.

Flow net is thoroughly constructed for every model under the effect of variation of various parameters that represent the important items that are mainly used for evaluating the efficiency of the cutoff under aprons. these flow nets are shown in figures from (5) to (11).

5. a. ANALYZING AND DISCUSSING THE RESULTS

These measurements, observations were documented and archived. They were analyzed, comprehended and plotted on graph. This graph is presented here. They are discussed from the point of view of energy dissipation ability and creep length as follows:

- Figure (12) presents the relation between F/R and θ of cutoff with seven different angles (0o, +15o, +30o, +45o, -15o, -30o and -45o) for Lhz/T=0.67.The apron provided with one cutoff and fixed at upstream.

On the other hand the table presents the effect of the cutoff inclination, as follows:

- Table (1) lists a summary to the effect of the cutoff inclination for runs 1 to 7 (One cutoff).

From the above figures, it was clear that:

- The rear face dissipation is increase when θF = +15o, +30o and +45o for cutoff.

- The front face dissipation is increase when θR = -15o, -30o and -45o for cutoff.
- The front face dissipation is bigger than the rear face dissipation When θ = 0 for cutoff.
- The front face dissipation is a same as the rear face dissipation When θF = +45o for cutoff.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the above investigation phases, the concluded aspects were listed and are represented on table (1). In general, the conclusions are as follows:

- For positive values of θ, the rear face dissipation is an increase when θF = +15o, +30o and +45o for cutoff.
- For negative values of θ, the front face dissipation is an increase when θR = -15o, -30o and -45o for cutoff.
- Based on the results, the best inclination angle of the cutoff could be estimated from fig. (5) At (F/R) = 1. When θF = +45o for cutoff.
- Based on the results, the worst inclination angle of the cutoff could be estimated from fig. (5) At (F/R) < 5. When θR = -45o for cutoff.

Based on the above, the following recommendations were foreseen and are given, as follows:

- More studies for the interaction between cutoffs and creep length for various cases of seepage under apron are still required to cover the different conditions in order to obtain reasonable forms that could help in achieving proper design of the aprons of hydraulic structures.
- A wider range of angles are to be tested.
- More studies are required for the efficiency of cutoffs in dissipating creep line energy with inclination angles under aprons of hydraulic Structures for the stratified soil is considered as two layers and more.

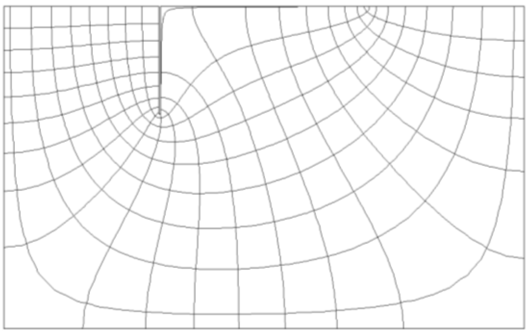

Figure (5): Distribution of the Head Pressure and Equipotential Lines RUN NO. (1)

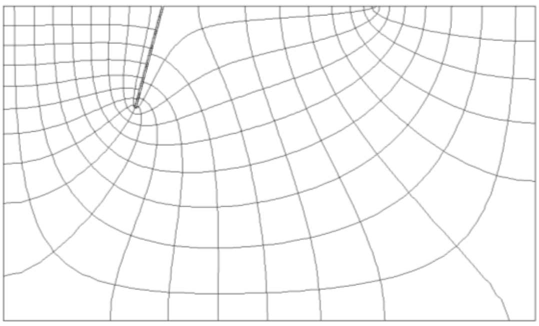

Figure (6): Distribution of the Head Pressure and Equipotential Lines RUN NO. (2)

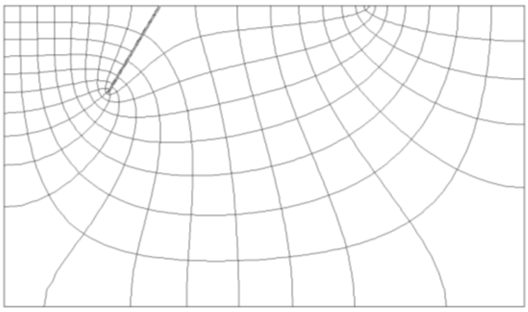

Figure (7): Distribution of the Head Pressure and Equipotential Lines RUN NO. (3)

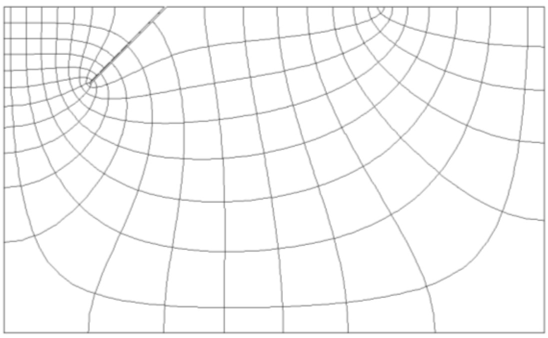

Figure (8): Distribution of the Head Pressure and Equipotential Lines RUN NO. (4)

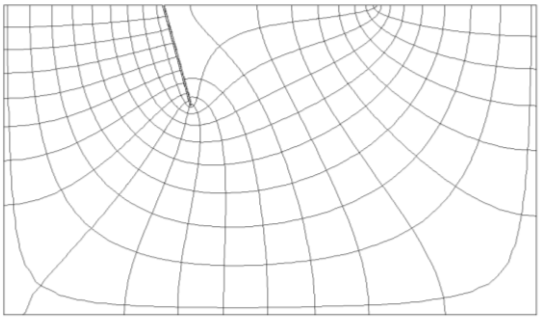

Figure (9): Distribution of the Head Pressure and Equipotential Lines RUN NO. (5)

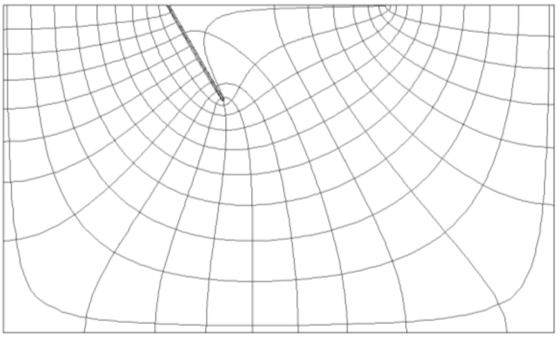

Figure (10): Distribution of the Head Pressure and Equipotential Lines RUN NO. (6)

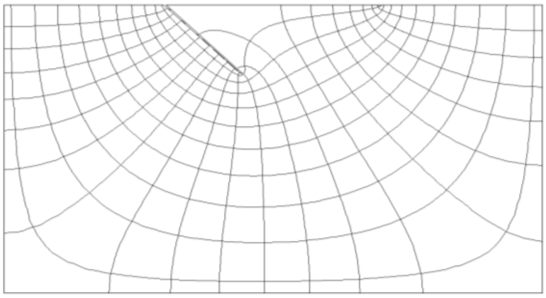

Figure (11): Distribution of the Head Pressure and Equipotential Lines RUN NO. (7)

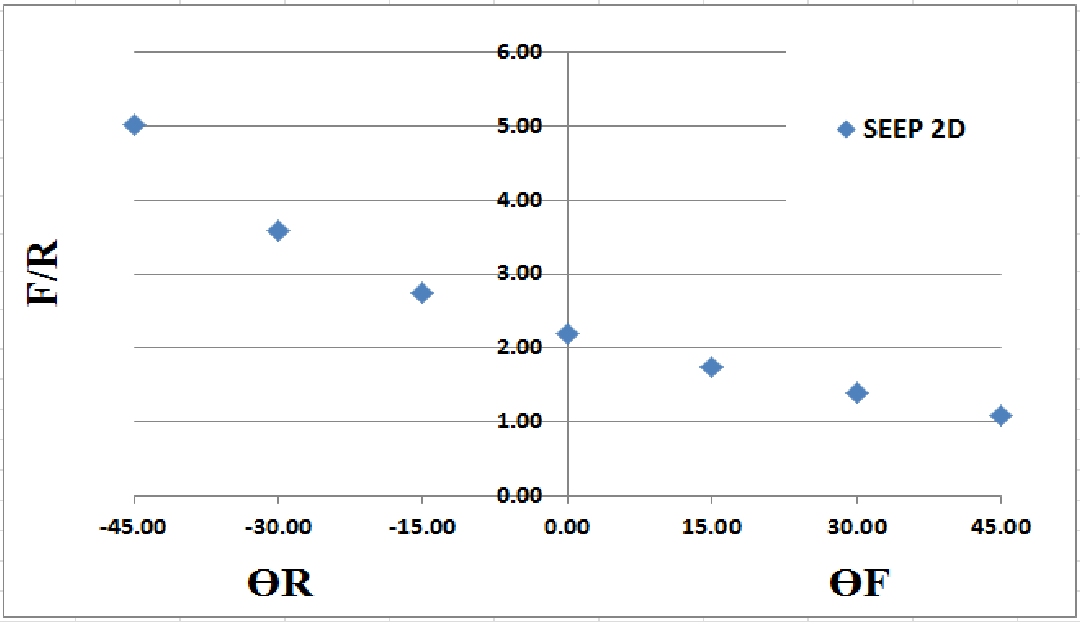

Figure (12) presents the relation between (F/R) and (θ) in front and rear direction.

Table (1) A summary to the effect of the inclination of cutoff

RUN NO.	H(VOLT)	D/T	θ		F/R
					SEEP 2D
1	**6**	**0.33**	**θ**	**0**	**2.18**
2	**6**	**0.33**	**θF**	**+15**	**1.74**

3	6	0.33	θF	+30	1.40
4	6	0.33	θF	+45	1.09
5	6	0.33	θR	-15	2.74
6	6	0.33	θR	-30	3.59
7	6	0.33	θR	-45	5.02

7. PRACTICAL APPLICATION

An examples is provided as a pragmatic candidature to the research functionality in practice. This examples advocates the application of the research results.

7. a. EXAMPLE

For the shown cross sectional elevation of a regulator with a one cutoff under apron:

D = 12.00 m T = 60 m H = 6.00 m Total Lhz = 40.00 m.

If the given dimensions are supposed to secure safety against undermining and piping according to Bligh's criterion, suggest amendments required to render it conforming with the (F/R) concept according to present work if the cutoff with inclination angle (0°, $+45^\circ$ and -45°).

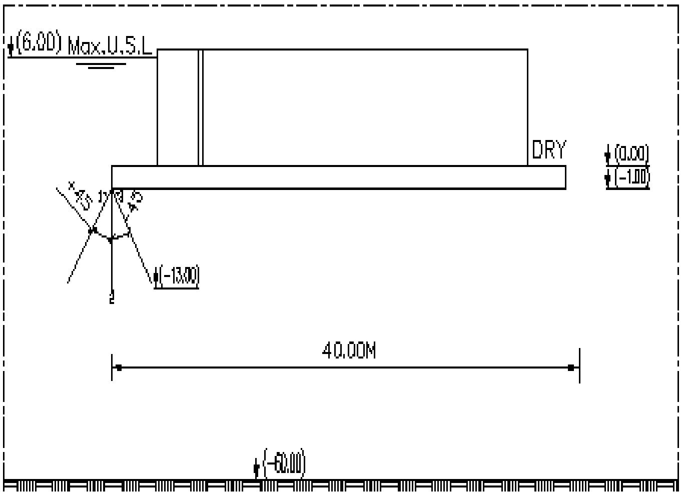

Fig. (13) Practical example

7. b. SOLUTION:

The creep length according to Bligh = Σ LV + Σ LH

Σ LV = 1+ (2 × 12) +1= 26 m

Σ LH = 40 m

The creep length according to Bligh (LW) = 66 m

1/CB = 6/66 = 1/ 11 (Hydraulic gradient for safety against undermining and piping).

From the chart, fig. (5-1):

X/ Lhz = 0, H/ Lhz = 6/40 = 0.15 and D/T = 12/60 = 0.20

For θ = 0, get F/R = 2.22

The creep length according to present work= Σ LV̄ + Σ LH

Σ LV̄ = 1+ (12 + 12/2.22) + 1= 19.41 m

Σ LH = 40 m

The creep length according to present work= 59.41 m

1/CB̄ = 6/59.41= 1/ 9.90 (Hydraulic gradient)

1/CB̄ < 1/CB (steeper)

Again, to guarantee a safe hydraulic gradient on the apron the creep length should be increase with increase in the cutoff depth

Head at (1) = 6-(1/9.90)*1 = 5.90 m

Head at (3) = 5.90-(1/9.90)*24 = 3.48 m

Difference in head between 1&3 = 5.90 – 3.48 = 2.42 m

F + R = 2.42, But F = 2.22 R

3.22 R = 2.42

R = 2.42/3.22 = 0.75 m

F = 2.22 * 0.75 = 1.67 m

F/D̄ = 1.67/D̄ = 1/CB = 1/ 11

D̄ = 1.67*11 = 18.37 m

Now, the modified creep length = 66 + (2*6.37) = 78.74 m

1/C (modified) = 6/78.74 = 1/13.12 instead of 1/ 11,

On the safe side with respect to undermining and piping.

Percent increase in cutoff depth = ((18.37-12)/12)*100 = 53 %

From the chart, fig. (5-1):

X/ Lhz = 0, H/ Lhz = 6/40 = 0.15 and D/T = 12/60 = 0.20

For θF = +45o, get F/R = 1.01

The creep length according to present work= Σ LV̄+ Σ LH

Σ LV̄= 1+ (12 + 12/1.01) +1= 25.88 m

Σ LH = 40 m

The creep length according to present work= 65.88 m

1/CB̄= 6/65.88 = 1/ 10.98 (Hydraulic gradient)

1/CB̄≈ 1/CB (equal)

Again, to guarantee a safe hydraulic gradient on the apron the creep length should be increase with increase in the cutoff depth

Head at (1) = 6-(1/10.98)*1 = 5.91 m

Head at (3) = 5.91-(1/10.98)*24 = 3.72 m

Difference in head between 1&3 = 5.91 – 3.72 = 2.19 m

F + R = 2.19, But F = 1.01 R

2.01 R = 2.19

R = 2.19/2.01 = 1.09 m

F = 1.01 * 1.09 = 1.10 m

F/D̄= 1.10/D̄= 1/CB = 1/ 11

D̄= 1.10*11 = 12.10 m

Now, the modified creep length = 66 + (2*0.10) = 66.20 m

1/C (modified) = 6/66.20 = 1/11.03 instead of 1/ 11,

On the safe side with respect to undermining and piping.

Percent increase in cutoff depth = ((12.10-12)/12)*100 = 0.8 %

From the chart, fig. (5-1):

X/ Lhz = 0, H/ Lhz = 6/40 = 0.15 and D/T = 12/60 = 0.20

For θR = - 45o, get F/R = 5.49

The creep length according to present work= Σ LV̄+ Σ LH

Σ LV̄= 1+ (12 + 12/5.49) + 1= 16.19 m

Σ LH = 40 m

The creep length according to present work= 56.19 m

1/CB̄= 6/56.19 = 1/ 9.37 (Hydraulic gradient)

1/CB̄< 1/CB (steeper)

Again, to guarantee a safe hydraulic gradient on the apron the creep length should be increase with increase in the cutoff depth

Head at (1) = 6-(1/9.37)*1 = 5.89 m

Head at (3) = 5.89-(1/9.37)*24 = 3.33 m

Difference in head between 1&3 = 5.89 – 3.33 = 2.56 m

F + R = 2.56, But F = 5.49 R

6.49 R = 2.56

R = 2.56/6.49 = 0.39 m

F = 5.49 * 0.39 = 2.14 m

F/D̄= 2.14/D̄= 1/CB = 1/ 11

D̄= 2.14*11 = 23.54 m

Now, the modified creep length = 66 + (2*11.54) = 89.08 m

1/C (modified) = 6/89.08 = 1/14.85 instead of 1/ 11,

On the safe side with respect to undermining and piping.

Percent increase in cutoff depth = ((23.54-12)/12)*100 = 96 %

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