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Effect of Seepage Barrier in Steady Seepage below Earthen Dam by Centrifuge Modelling

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Abstract. Modeling of prototype geo-structures such as slopes, embankments, retaining walls, piled foundations, and tunnels have been effectively done in geotechnical centrifuge. Approaches of centrifuge modeling have facilitated the evaluation of seepage and deformation in the embankments and also considered a powerful tool to examine the failure mechanisms. In this context a model dam, made of clayey soil based on cross-sections of an earthen dam, in South 24 Parganas, West Bengal, India have been studied with experimental modeling by centrifuge. The present study, therefore, have been carried out to analyze steady seepage condition in case of a water front earthen embankment dam. Experimental study has been performed by centrifuge modeling, considering Scale factor N= 100g, g being acceleration due to gravity. The model has been rotated at a speed of 400 rpm. In the experimental simulation, phreatic line, flow net and stability against steady state seepage in terms of factor of safety, have been obtained. The effectiveness of sheet pile as seepage barrier with varying sheet pile length and position for all cases, have been studied, with variation of sheet pile length of 5m, 10m, 15m and 20m varying the sheet pile position at *B*/8, 2*B*/8 and 3*B*/8 positions from the downstream end, *B* being the width of the dam. It has been observed that sheet pile length has significant effect on fluid flow vector, factor of safety along the sheet pile.

Keywords: Model tests; Centrifuge, Piping, phreatic line, flow net.

1 Introduction

The effect of seepage water flow causes loss of inter-particle force leading to decrease in the skeleton stress which triggers dam failures as well as induced slope instability. According to studies, approximately 41.6 % of dam failures are related to internal erosion (Foster et al., 2000). A comprehensive discussion on the mechanisms of piping and internal erosion in dams was presented by McCook (2004). Fell and Wan (2005) presented methods for estimating the probability of failure of embankment dams by internal erosion, piping within the foundation, and piping from the embankment to the foundation**.** Cut-off walls are used to prevent seepage in dams as long-term effective solution.

Approaches of centrifuge modeling have facilitated the evaluation of seepage and deformation in the embankments and also considered a powerful tool to examine the failure mechanisms. Centrifuge modeling generate the real stress field and at the same time faster seepage flow. Centrifuge modelling is a technique which involves physical modelling to capture the correct failure mechanism in the boundary value problems with the help of digital cameras.

The basic principle of a geotechnical centrifuge is to enhance gravity field by the same geometric factor N, relative to the normal earth's gravity field. In a centrifuge small-scale models are tested in a gravity field, which is linear function of the distance from the center of rotation. Thus, the gravity field varies linearly with radius from the center of rotation and as a square of the angular velocity θ' of the centrifuge.

A seepage study was carried out for the western dyke of Wallace dam (Lake Oconee, Georgia, USA) by Aral and Maslia (1983). It was observed that, flow vector to the chimney drain showed that it was very effective in reducing seepage pressures.

Davies and Parry (1985) conducted centrifuge test to check the performance of low embankment founded on soft clay soil during and after the construction. They monitored displacement and pore pressure variation to observe the progressive failure. They carried out total and effective stress analyses of the embankment stability. Pore pressure was studied increased as much as 18% after the end of the construction. Perri et al (2012) analyzed the influence of the pore water pressures in the calculated factor of safety of an embankment with and without cut off wall in steady state condition of full flooding stage using finite element method. They observed that using cut off wall there was significant decrease of seepage gradient and thereby increase of Factor of Safety.

The present study has taken up a field problem in the Sunderban region of West-Bengal, India where 3520 kms of earthen embankments, used as protective structures of water head of 3-4.5 meters. The sunderban along the Bay of Bengal has evolved between through quaternary sediments deposited mainly carried by the complex network of tidal rivers. It is part of the tide dominated lower deltaic plain.

The purpose of this study is to find the effect of cut off wall beneath an earthen dam for analyzing the failure by the use of centrifuge modeling as a tool. Experimental testing procedures implemented as part of a recent centrifuge study undertaken to evaluate the performance of slopes at failure. In the experimental simulation, phreatic line, flow net and stability against steady state seepage in terms of factor of safety, have been obtained. The effectiveness of sheet pile as seepage barrier, varying sheet pile length and position for all cases, have been studied, with variation of sheet pile length of 5m, 10m, 15m and 20m varying the sheet pile position at *B*/8, 2*B*/8 and 3*B*/8 positions from the downstream end, *B* being the width of the dam. It has been observed that sheet pile length has significant effect on pore pressure variation along the sheet pile. It also evaluated by experimental modeling that seepage failure is more likely to occur at the bottom of cut-off walls because of magnitude of high seepage velocity. The average seepage gradient of the embankment foundation decreases with the increase of the height of cut-off walls, and the seepage gradient at the bottom of cut-off walls is always maximum along the seepage contour line.

2. Model for the Study

The stratification of subsoil of the selected area of South 24 parganas, West Bengal have been obtained from study of bore log data sheets of different locations. The cross-sectional details of existing embankment of typical model dam have been presented in Figure. 1. The study have been done for working head of 3.0m in steady state condition. Table 1 presents sheet pile properties for steady seepage and transient condition.

Table 1. Properties of sheet pile material

Area of cross section per meter	**0.03**
Moment of Inertia per meter (N-m/m)	0.00225
E_{steel} (N/m^2)	2×10^{11}

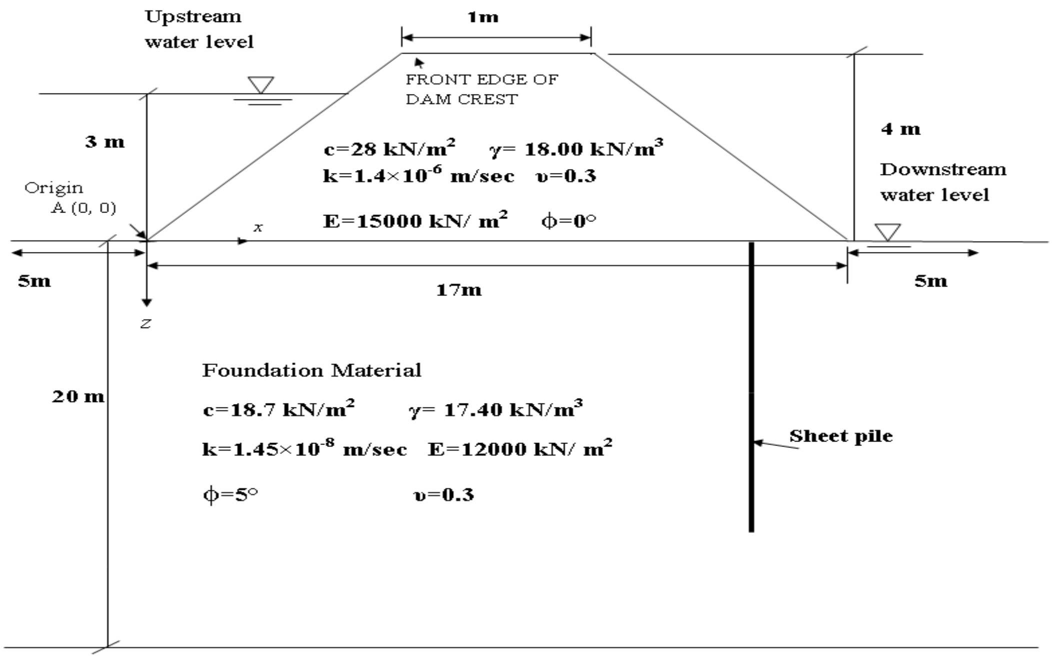

Fig. 1. Schematic Diagram of Model Embankment for Centrifuge Modeling

3 Centrifuge modeling

3.1 Description of Centrifuge

This geotechnical centrifuge at the Geotechnical Engineering Laboratory, Civil Engineering Department, Jadavpur is a 4 pole 500 Hz induction motor with 3 phase system and of 1.5m radius with maximum payload capacity 8.5 tons at 400g. The diameter of the centrifuge is 0.55m. The turner beam carries scaled model at one end and a counter weight at the other, each mounted on a swing platform has been described in Figure 2. In the geotechnical centrifuge considering 100g the calculated rpm is 404 rpm using eq. (1)

$$\omega^2 R = ng \tag{1}$$

$$\omega = \sqrt{\frac{100 \times 9.81}{0.55}} = 42.23 \text{ rad/s} = 404\text{rpm} = 400\text{rpm (say)}$$

In centrifuge modelling a rotating soil body mounted on a geotechnical centrifuge to represent a scale model of a given prototype which is to be modelled.

The ratio of linear prototype dimension to the centrifuge model when *N*, then the ratio of area is N^2 and volume N^3. It has been indicated from the scaling relation that the forces in the prototype is N^2 times and moments N^3 of the corresponding model. In the experiment it was necessary to design model wall to a similar stiffness of prototype per unit width (*EI*). The ratio of stiffness of prototype is N^3 times of that of the model. In the present study *N* has been adopted as 100. The model was 1/100 of the prototype linear dimension, and the model acceleration was 100 times of normal terrestrial gravity. In order to determine the true stiffness *(EI*) of the modeled sheet pile wall, $EI_{model}=EI_{prototype}/N^3$

Steel sheet pile has been considered as protype structure. Modulus of Elasticity of Steel Sheet pile ($E_{prototype}$) = 2×10^{11} N/m^2. Moment of Inertia per meter of steel sheet pile ($I_{prototype}$)=0.00225 m^3. In the present seepage study Perspex sheet has been used as modeled sheet pile. Modulus of Elasticity (E_{model}) of the Perspex= 2.0×10^9 Pa. Moment of Inertia per unit width (*I*) of a rectangular cross section is $\frac{(h')^3}{12}$, where *h'* is the section depth. In the present experimental study 20 cm length of Perspex when modeled as sheet pile, Moment of Inertia per unit width (I_{model}) = 2.49×10^{-7} m^3/m.

$EI_{model}=2.0\times10^9\times2.49\times10^{-7}=498$ N-m/m.

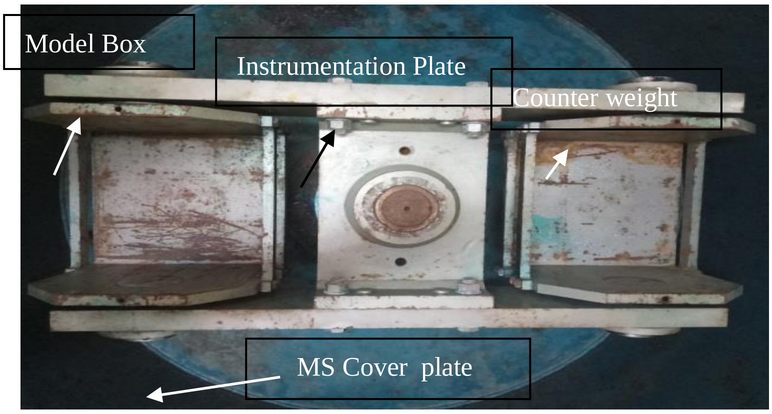

Fig. 2. Top view of the Geotechnical Centrifuge with component details.

3.2 Experimental set up

3.2.1 Test box

The scaled model and the counter weight have been mounted at two ends of a swing platform. A seepage square tank has been fabricated with steel frame, supporting 10 mm thick transparent Perspex sheet on all sides to simulate three dimensional conditions. The test box has dimension with 26.7cm (Length) by 26.7cm (Width) by 26.7cm (Height).

Water supply arrangement using valve

The reservoir has been placed above the top of tank and flow from reservoir to tank has taken by virtue of centrifugal acceleration. In this study Arduino ATMEGA 2560 board has been used to control inlet and outlet valve. An artificial tide control circuit to provide an interface to complete the experimental work. The circuit has been processed by providing internal energy source and has been controlled by infrared remote.

Digital image processing

With the help of digital cameras, it has been possible to capture the digital image of the centrifuge model by mounting camera on the model and viewing the cross-section through transparent side. To fulfill the objective Raspberry pi 3B model has been used with a preinstalled Wi-Fi hardware module

Construction of Model embankment

Embankment model was formed as a typical earthen Embankment with desired dimensions and properties and a centrifuge scale of N= 100, has been shown in Fig 3.
A 20 cm thick bed was constructed in five layers was achieved by blows from a Standard Proctor Hammer of 4.5 kg falling over a height of 300 mm. The number of blows was adjusted as per density requirement. The targeted density was 95 percent of Standard Proctor density. The Soil properties of embankment as per IS classification is ML. The side slopes were kept at 2(H):1(V). Sheet piles were used as a cutoff in the experimental model in centrifuge. Table 2 represents numerical analysis for current study considering variation of parameters of sheet pile length and positions under steady state conditions.

Table 2. List of centrifuge modeling cases under steady state

Sl. no.	Sheet pile length in meter	Sheet pile position from Downstream end
1	N.A	N.A
2	5	$B/8$
3	10	
4.	15	
5	20	
6	5	$2B/8$
7	10	
8	15	
9	20	
10	5	$3B/8$
11	10	
12	15	
13	20	

Where, *B*= Base width of dam Based on the images obtained from the experiments phreatic line and flow net has been obtained for each experimental model against steady state seepage condition.

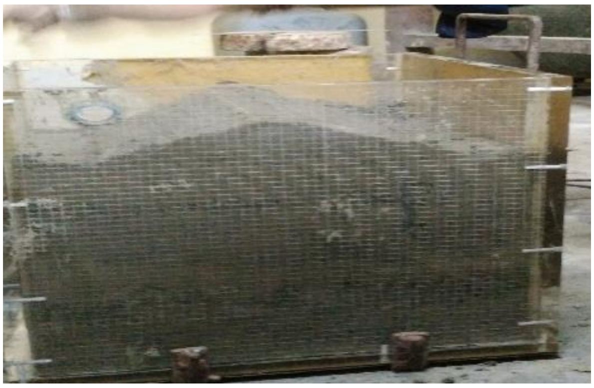

Fig. 3. Top view of the Geotechnical Centrifuge with component details.

4 Results and Discussion

During steady state tests with working head of 3.0 m the flow net pattern has been shown in Fig. 4 for embankment. The variation of the flow net in upstream side with respect to working head condition has also been shown in the respective figures. Points A, B, C, D, E has been marked with progress of time to illustrate the propagation of flow.

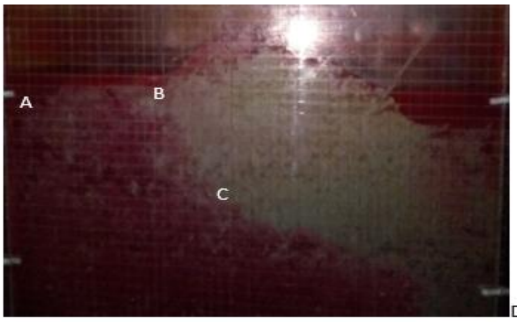

Fig. 4. Experimental output of embankment during steady state condition without cutoff

4.1 Flow net Pattern

An attempt has been made to observe the effect of location and length of sheet pile, used, as seepage cutoff. The results of the tests have been obtained by processing the captured image through MATLAB programming PIV High-resolution images that can be obtained from centrifuge model tests have been processed to give the fluid flow vector by Particle Image velocimetry (PIV) technique. PIV is a non-intrusive velocity field mapping technique that makes use of captured optical images to produce instantaneous vector measurement. Furthermore, PIV allows for the visualization of magnitudes and gives values the x-y components of velocity for the flow different points, at different times in matrix form. The flow net has been developed for different cases under steady seepage condition and also in different time intervals by image processing through PIV. The experimentally obtained phreatic surface, flow net and pattern of fluid flow vector of an embankment has been shown in Figure 5. The experimentally obtained typical phreatic surface, flow net and pattern of fluid flow vector in an embankment for *B*/8 position 10m length and 15 length sheet pile has been shown for in Fig. 7 and Fig. 8 respectively. A typical phreatic surface and flow net has been shown in Fig. 6 for Sheet pile at 3*B*/8 position 10m length.

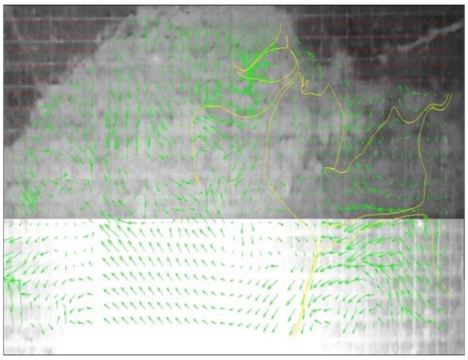

Fig. 5. Phreatic Surface and flow net for steady state condition

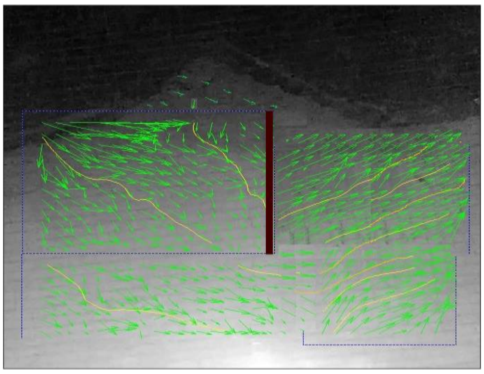

Fig. 6. Flow net and fluid flow vector for 3*B*/8 position 10m long sheet pile

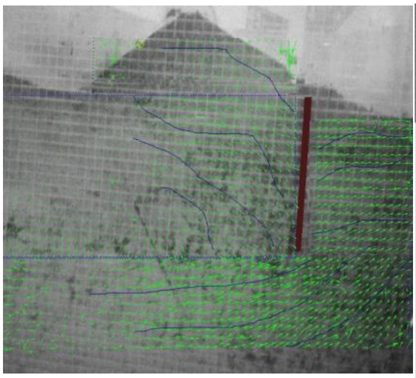

Fig. 7. Flow net and fluid flow vector for *B*/8 position 15m long sheet pile

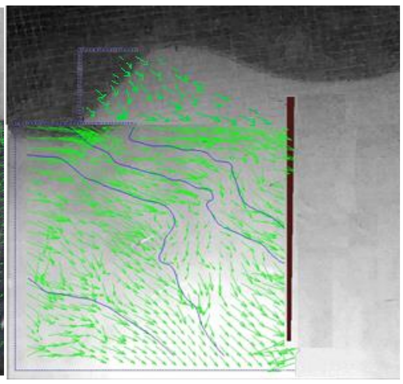

Fig. 8. Flow net and fluid flow vector *B*/8 position 10m long sheet pile

It has been observed from Fig.6 to Fig.8 that that sheet pile acts as a fluid barrier effectively. It has been observed that as the Sheet pile moves away from the downstream end the field of the flow net near the downstream end is becoming more or more effective. When sheet pile is shifted towards the downstream end then the average dimension of last element of flow line is decreases. It also observed from that for any fixed position when sheet pile length increases seepage path increases. It has been observed that for any fixed position of sheet pile exit gradient reduces with sheet pile length for any particular position of sheet pile. As Sheet pile length increases seepage path increase which reduces the exit gradient. It has been obtained that, when sheet pile length increases by 30% of bottom width of dam the exit gradient decreases 9.97%. Furthermore, it evaluated that, If the sheet pile length increases 59% of bottom width of dam the exit gradient decreases 18.16%. Therefore, from the modeling of seepage analysis it is evaluated that if the sheet pile length increases 30% to 59% of bottom width of dam the exit gradient decreases of exit gradient is almost proportional to the pile length. From experimental modeling of seepage analysis, it is evaluated that exit gradient decreases by 8.17% if the sheet pile position is shifted from 14.25% of bottom width of dam from the downstream end.

4.2 Fluid flow vector

An attempt has been made in this section to study the development of fluid flow vector with variation of time without and with sheet pile depending on sheet pile lengths and positions. In each case fluid flow vectors have been plotted along the horizontal profile at distances of 5m from top of the dam to study its variation within the dam body as well as foundation of the dam. The purpose of this fluid flow vector study is to investigate the effectiveness of sheet pile against erosion caused by piping. Distance and velocity components in vertical direction have been plotted in the form of pixel/frame through PIV analysis.

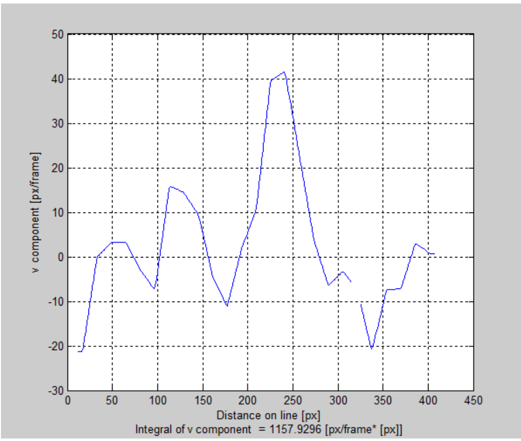

Fig. 9. Fluid flow vector in vertical direction for sheet pile length 10m at fixed position of *B*/8

Fig. 9 represent a typical figure of fluid flow vector in pixel form analyzed by PIV for 10m length of sheet pile positioned at *B*/8 position from downstream end along the horizontal direction. Fig. 10 represent a typical figure of fluid flow vector analyzed by PIV for different length of sheet pile positioned at 3*B*/8 position from downstream end along the horizontal direction.

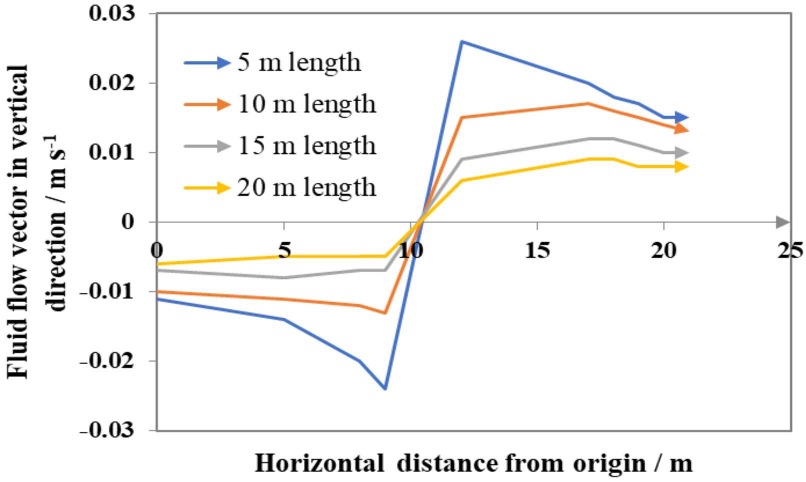

Fig. 10. Fluid flow vector in vertical direction for different sheet pile length at fixed position of 3*B*/8

It is observed from Fig. 9. and Fig. 10 that maximum flow vector occurs at sheet pile position. This maximum value is highest for 3*B*/8 position of sheet pile from down-stream end. For each case the flow vector is increased at the sheet pile position indicating vertical flow along sheet pile. The negative signs arise due to fluid flow in the downward direction along the length of sheet pile. At the position of sheet pile there is an abrupt jump of fluid flow vector. At the upstream side of sheet pile, fluid flow vector decreases along the length and at the downstream side of sheet pile it increases with length. It has also been observed from Fig. 10 that decrease of fluid flow vector for 20m length of sheet pile on the downstream end is 30% less compared to 5m length of sheet pile and 13% less compared to 15m length of sheet pile at 3*B*/8 position. It has also been observed that effect of sheet pile position on fluid flow vector on the downstream end is minimal.

4.3 Stability against piping

Fig. 11 shows the variation of factor of safety against piping with sheet pile lengths at different position.

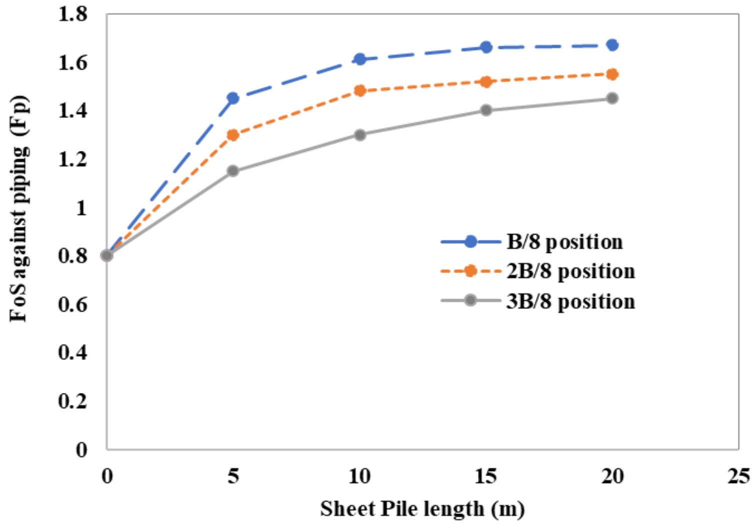

Fig. 11. Variation of factor of safety with sheet pile position and length

It is observed that for a fixed sheet pile length, factor of safety against piping decreases when sheet pile position moves away from downstream end. When sheet pile moves from downstream end exit gradient increases and chance of piping is reduced. As sheet pile position is shifted towards the downstream end, the average flow length of the extreme field of flow net at downstream end increases which causes reduction in exit gradient. Thus, the factor of safety against piping increases. As sheet pile length increases seepage path increases, reducing the exit gradient and thus also reducing the chance of piping failure. Similar observation was made by Perri et al (2012). For increase of length of sheet pile, as creep length increases, exit gradient reduces and thereby factor of safety against piping increases. It has been seen that at 5m of sheet pile at *B*/8 position factor of safety against piping increases up to 22.00% compared to 3*B*/8 position whereas this is approximately 18.18% for 2*B*/8 position, compared to 3*B*/8 position. It is also observed that factor of safety against piping increases by 20% to 30% due to increase of sheet pile length.

4 Conclusions

The following conclusions may be drawn from this present study:

1. Effectiveness of seepage cut off has been appropriately studied in the centrifuge modeling through image-based analysis.
2. Sheet pile length increases seepage path, which reduces the exit gradient. In case of increase of sheet pile length by 30% of bottom width of dam the exit gradient

decreases 9.97%. Furthermore, when sheet pile length increases 59% of bottom width of dam the exit gradient decreases 18.16%.

3. Exit gradient decreases by 8.17% if the sheet pile position is shifted from 14.25% of bottom width of dam from the downstream end.
4. For any fixed position when sheet pile length increases seepage path increases. Fluid flow vector decreases as sheet pile moves towards downstream end and it is maximum for least length and flow vector reduces with increase of sheet pile length studied through experimental modeling.
5. Fluid flow vector for 20m length of sheet pile on the downstream end decreases 30% less compared to 5m length of sheet pile and 13% less compared to 15m length of sheet pile for any particular position of sheet pile.
6. Factor of safety against piping decreases 18% when sheet pile position moves away from downstream end for a fixed sheet pile length. As the length of the sheet pile increases factor of safety against piping also increases. In case of piping, it is more predominant due to increase of creep length. Factor of safety against piping increases by 20% to 30% due to increase of sheet pile length.

References

1. Aral Mustafa M., and Maslia Morris L. (1983), "Unsteady Seepage Analysis of Wallace Dam", J. Hydraul. Eng.109, pp.809-826
2. Davies M.C.R. and Parry R.H.G. (1985), "Centrifuge Modelling of Embankments on Clay Foundations" Soils and Foundations Vol.25, No.4, 19-36, Dec. 1985, Japanese Society of Soil Mechanics and Foundation Engineering.
3. Perri., J,F, and Shewbridge. S, E, and Cobos-Roa.,D, A, and Green.,R, K, (2012), "Steady State Seepage Pore Water Pressures Influence in the Slope Stability Analysis of Levees",*GeoCongress , ASCE.*
4. Foster, M., Fell, R. & Spannagle, M., 2000. The statistics of embankment dam failures and accidents. Canadian Geotechnical Journal, 37(10), pp.1000–1024.
5. Fell, R., MacGregor, P., Stapledon, D., & Bell, G., 2005. Geotechnical Engineering of Dams.