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Deformation analysis of suspended type cut off wall of diversion structures

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ABSTRACT

Numerical study is carried out to analyse the behaviour of cut off walls in sandy soil, under constant differential pressure head, by varying its location from upstream end to downstream end. The deformation and bending moment in cut off wall are at their lowest magnitude when the cut off wall is positioned at upstream end. The cut off wall is subjected to second lowest deformation, when it is positioned at downstream end. The maximum deformation occurs, when the cut off wall is positioned at 0.60 times the total width of diversion dam from upstream end. The seepage rate in the diversion dam is highest when the cut off wall is positioned at centre of the diversion dam. The seepage rate in the diversion dam is having direct relation with the maximum displacement and maximum bending moment. The seepage force found to be more predominant than the pressure gradient and active pore pressure variations in deforming the cut off walls of diversion dams.

1. Introduction

The hydraulic structure like diversion structures are constructed across river in permeable foundations. The impounded water on the upstream side of diversion structures seep through the foundation soil (see Fig. 1). This seepage flow tends to destabilize the diversion structure. Therefore, the seepage through foundation soil measured and analyzed with the parameters; seepage rate, uplift force and exit gradient. These parameters are controlled to increase the factor of safety of the diversion structure. Formation of cut off wall is the one of the controlling technique of these destabilizing parameters. These cut off walls formed to certain depth of pervious stratum, not to its full depth. Hence, these walls act as partial seepage barriers and looks like, as if, suspended from the apron. Seepage flow from upstream of diversion structure to downstream of it, due to the differential pressure head created by the impounded water. This line of seepage is creep line and length of this seepage path is creep length.

Bligh [1] introduced the creep length theory for seepage passing from upstream to downstream. According to Bligh [1], creep length is the first line of contact on foundation of structure. This creep length theory, also states that the loss in energy occurs along the creep length uniformly, so the uplift pressure distribution along the creep length is uniform irrespective of the vertical or horizontal creep path. Lane [2] has brought advancement over the Bligh's [1] creep length theory and assigned different weightage to horizontal and vertical creep length. Lane [2] prescribed 0.33 weightage for horizontal path and 1.0 weightage for vertical path. The total creep length included vertical and horizontal percolation length based on the weightage. Khosla et al [3] introduced an improved method to assess the uplift pressure on hydraulic structures with pervious foundations. This method is based on concept of "flow net" comprising seepage lines (streamline flow from upstream to downstream) and equipotential lines crossing each other orthogonally.

Various research studies carried out using both numerical and experimental models to study the cut off walls for their hydraulic behaviors for various changes in structural configurations and soil parameters. Moharami et al [4], Kumar et al. [5], King and Collins [6], Shayan and Tokaldany [7] and Alsenousi and Mohamed [8] conducted studies using various configuration of cut off walls. They studied the effects on seepage rate, exit gradient variations and uplift pressure variations for various configuration of cut off wall. As these parameters affects the factor of safety of the structure, they need due attention while designing diversion structures. However, these studies orient on the hydraulic requirements of the cut off walls, not on the structural requirements of it.

Rice and Duncan [9] reported that the seepage barriers likely to develop crack due to the differential water pressure head acting on the barrier. Rice and Duncan [10] also reported that the pore pressure regime

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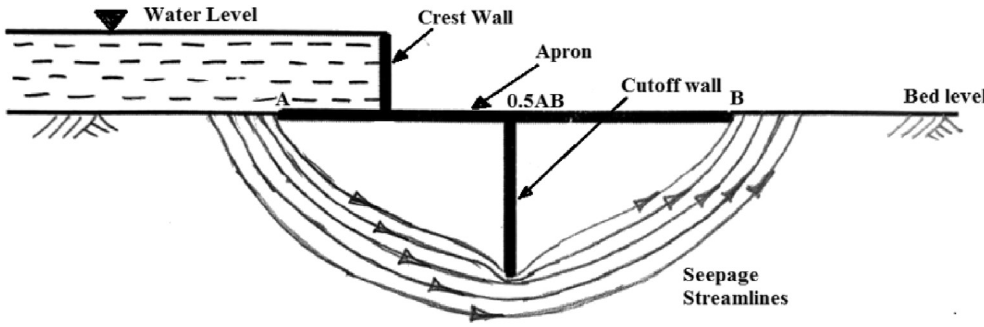


Fig. 1. Typical diversion dam model.

changes deform the rigid seepage barrier and likely to develop cracks in the barriers. They reported that change in pore pressure regime and differential pressure head acting on the cut off walls could deform them and inflict failure.

Departing from usual study on hydraulic behavior of cut off walls, Sivakumar et al. [11], studied the deformation behavior of cut off walls under varying differential pressure head, relative density of soil and soil modulus. In their study they concluded that by increasing the differential pressure head, the deformation in cut off wall increases. Increase in relative density and soil modulus, decreases the deformation in cut off walls. In all the cases, even though the upstream cut off is located in higher pressure zone, the downstream cut off wall always subjected to deformation higher than that of upstream cut off wall. Sivakumar et al [12] reported the behavior of downstream cut off wall using the numerical models of diversion dam for depth variations in upstream cut off wall. In their study, they concluded that the seepage force is more predominant than the pore pressure regime changes and ground water head, in deforming the cut off wall.

Research study on cut off wall for their structural response for various changes in structural configurations and soil parameters is a gray area, which needs adequate attention. Hence, this study is primarily oriented to understand the structural deformation behaviors of cut off wall for various configurations at constant differential pressure head. At constant differential pressure head with chosen soil parameters, the cut off wall of defined depth is allowed to vary its location from upstream end to downstream end. The deformation behavior of cut off wall for varying its location from upstream end to downstream end is studied using numerical model.

1.1. Governing equations

Manna et al [13] presented the general governing equation as given in Eq. (1) for seepage in 2D plane.

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+q=\frac{\partial V}{\partial t} \tag{1}$$

Where Kx denotes the permeability of soil in x directions and Ky denotes the permeability of soil in y directions. q is the flux in to the boundary, V is the total volume of water, t is the time interval and h is the differential water pressure head applied. This equation satisfies flow of continuity, i.e. difference between volume of water entering and volume of water leaving the point of consideration is equal to the volume change in storage of water. This condition prevails during unsteady flow condition. However, in steady state flow condition, the flux entering and exiting the boundary is equal and hence there is no volume change within boundary. As there is no change in volume, Eq. (1) equals to zero. The equation applicable for steady state condition is given in Eq. (2).

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+q=0 \tag{2}$$

1.2. Boundary conditions

The boundary conditions are required to be fixed to analyze the problem. In our study of steady state flow condition, the following boundary conditions are applied. In reservoir side, the water head is a known value i.e. applied water pressure head. Hence, the pressure head or piezo head is known in all points of the boundary and the same is given in Eq. (3).

$$H=\frac{P}{\gamma}+y \tag{3}$$

Where, H – the total head
P – Pore water pressure
γ– Unit weight of water
y – Elevation above arbitrary datum

The bottom boundary assumed to be impervious to represent the real condition. The bottom boundary has zero value of vertical velocity, i.e., no seepage through the boundary.

2. Model

Two-dimensional model is prepared using FEM software. There are numerous FEM Software available in the market for analysis. Some of the notable software are MODFLOW, SEEP/W, ANSYS, PLAXIS, PDEase2D, SVFLUX, etc., Plaxis 2D is one of the user-friendly software used for analyzing deformation, stability and groundwater flow. As the soil is a multiphase material, it requires utmost care in dealing with hydrostatic and non-hydrostatic pore pressure in the soil. Plaxis software is designed to make it suitable for groundwater flow calculations and simulate its non-linear behavior. Therefore, Plaxis 2D is used to analyze this model with steady state condition in plane strain configuration. The structural elements of this chosen model are given in Table 1. These structural parameters are based on the structural components of a barrage at Cauvery River. The Standard Penetration Test was carried out at the Cauvery Barrage site and the N values were obtained. Using Bowel's correlations for the N values obtained, required soil parameters were arrived. The parameters of chosen soil are given in Table 2. The chosen sandy soil is assumed to be isotropic having $Kx = Ky = K$. i.e., the mean value of permeability in entire stratum is same. Mohr - Coulomb model is adapted for this study.

Table 1
Parameters of structural components.

Structural components	EA in kN	EI in kNm^2	thickness in m	depth in m	ν	w in kN/m
Cut off Walls	1.55E+07	4.51E+05	0.60	9.00	0.00	10.00
Apron	2.91E+10	5.44E+06	1.50	30.00	0.15	8.20
Crest Wall	4.85E+07	2.50E+07	2.50	5.00	0.15	8.20

Table 2
Soil parameters.

Sl No	Depth in m	N Value	Relative Density in % D_r	Unit weight in KN/m3 γ_{unsat}	Unit weight in KN/m3 γ_{sat}	Dilatancy Angle in degree ψ	Angle of internal friction in degree - φ	Youngs Modulus KN/m^2 E_{ref}	Cohesion in KN/m^2 C_{ref}	Poisson Ratioν	Permeability m/day K
1	5.25	32	65	17.10	21.25	14.00	36.00	23500	1.00	0.30	7.25

The structural elements of the model are created using plate tool in Plaxis. Standard fixity condition is applied. Interface elements are provided based on soil and structure contacts. As this model involves active pore pressure coupled with effective stresses, the initial conditions are specified in Water Condition mode for the initial stresses. This initial water pressure can be created by using the phreatic levels. The soil cluster in the material data set is specified as Drained; with sand as cluster material, no excess pore pressure is created.

Khosla et al [3] presented the "Method of independent variable" (shown in Fig. 2) to determine the uplift pressure on hydraulic structures with pervious foundations. In this method, the complex structures are broken into small simple structures and the same is analyzed. Then corrections applied to make them more relevant for complex structures. The Pressure head $\varnothing E$, $\varnothing D$ *and* $\varnothing C$ in the respective critical points E, D and C are obtained using the following Eqs. (4), (5), and (6) respectively as prescribed by Khosla et al:

At E $$\varnothing E = \frac{1}{\pi}\cos^{-1}\left\{\frac{\lambda_1 - 1}{\lambda}\right\} \quad (4)$$

At D $$\varnothing D = \frac{1}{\pi}\cos^{-1}\left\{\frac{\lambda_1}{\lambda}\right\} \quad (5)$$

At C $$\varnothing C = \frac{1}{\pi}\cos^{-1}\left\{\frac{\lambda_1 + 1}{\lambda}\right\} \quad (6)$$

Where, λ_1 and λ are calculated using Eqs. (7) and (8). The values of α_1 and α_2 arrived based on Eqs. (9) and (10). The measure of b_1, b_2 and d are represented in Fig. 2.

$$\lambda_1 = \frac{\sqrt[2]{1+\alpha_1{}^2} - \sqrt[2]{1+\alpha_2{}^2}}{2} \quad (7)$$

$$\lambda = \frac{\sqrt[2]{1+\alpha_1{}^2} + \sqrt[2]{1+\alpha_2{}^2}}{2} \quad (8)$$

$$\alpha_2 = \frac{b_2}{d} \quad (9)$$

$$\alpha_1 = \frac{b_1}{d} \quad (10)$$

The prepared model is subjected to the numerical study using Plaxis 2D and analytical study using Khosla et al., analytical solutions. The results obtained from both numerical and analytical solutions are plotted in Fig. 3. The pressure head at critical points C, D and E are compared. From the plot, it can be understood that both numerical results and analytical solutions are close to each other with in the permissible limits. Therefore, the model prepared for this study is appropriate.

Analysis carried out by varying the location of cut off wall from upstream end to downstream end in suitable intervals. A constant differential pressure head is applied. At this constant applied pressure, the behaviours of cut off wall for varying its location are studied. The obtained results are plotted and behaviours are analysed. Numerical model of diversion dam is shown in Fig. 4. The deformed mesh, ground water head plot and pore pressure diagram of diversion dam is shown in Figs. 5, 6 and 7 respectively.

3. Results and discussions

Analysis of numerical model carried out by varying the location of cut off wall from upstream end to downstream end. Trials carried out by positioning the cut off wall at upstream end A, at 0.2AB, 0.4AB, 0.5AB, 0.53AB, 0.57AB, 0.6AB, 0.8AB and at downstream end B, where AB is total width of diversion dam from upstream end to downstream end. A constant differential pressure of 5m water head, applied in all the cases. Except the location of cut off wall, all other soil and structural parameters kept constant. The obtained results of numerical analysis are studied.

3.1. Displacement of cut off wall

By varying the location of the cut off wall from upstream end to downstream end, changes in displacement patterns of the cut off wall are studied. The displacements of cut off wall for varying its locations are shown in Fig. 8. Normalized displacements are shown in Fig. 9. These plots show that the magnitude of maximum displacement increases up to the location 0.6AB; beyond that, the maximum displacement starts reducing. When the cut off wall is located at A, the point of occurrence of maximum displacement is at top end of the cut off wall. By shifting the cut off wall towards downstream end, the point of occurrence of maximum displacement shifts downward. The maximum of maximum displacement in the cut off wall occurs when the cut off wall is located at 0.6AB from upstream end. The lowest maximum displacement in cut off wall occurs when the wall is located at the upstream end. When it is

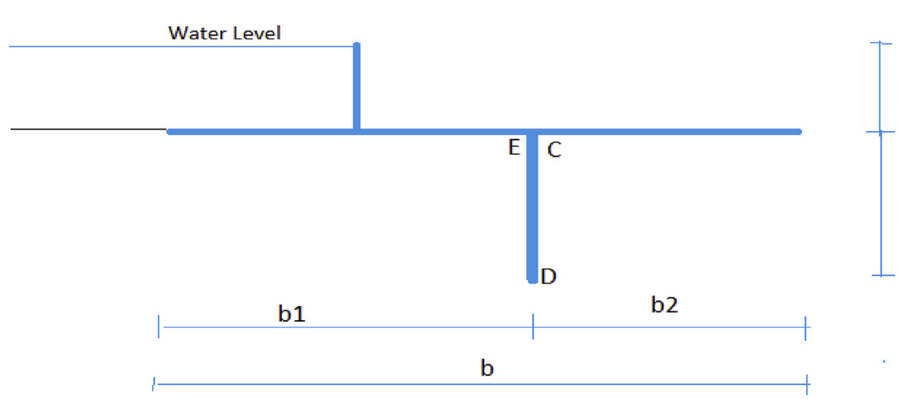


Fig. 2. Method of independent variables.

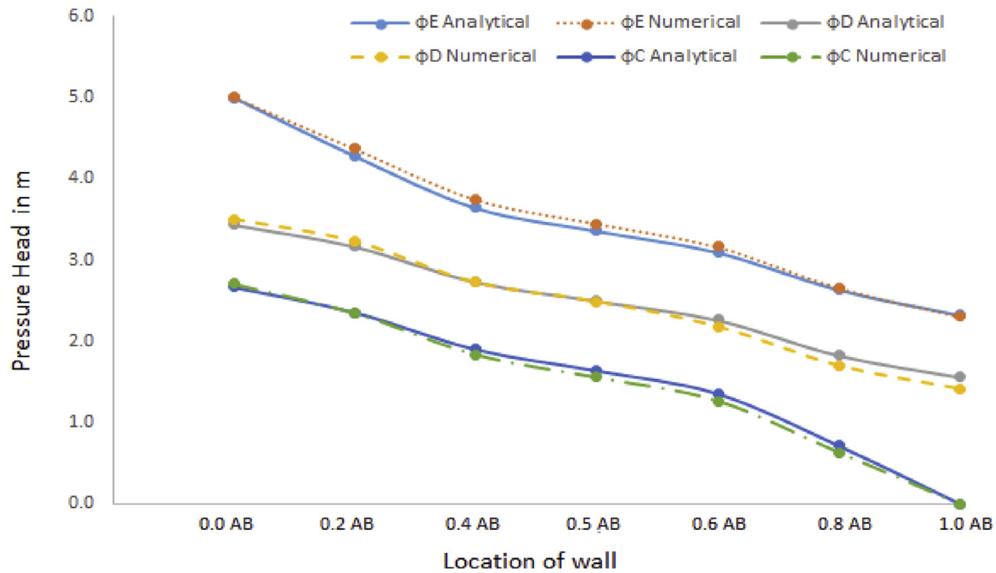


Fig. 3. Comparison of Numerical results and Analytical solutions.

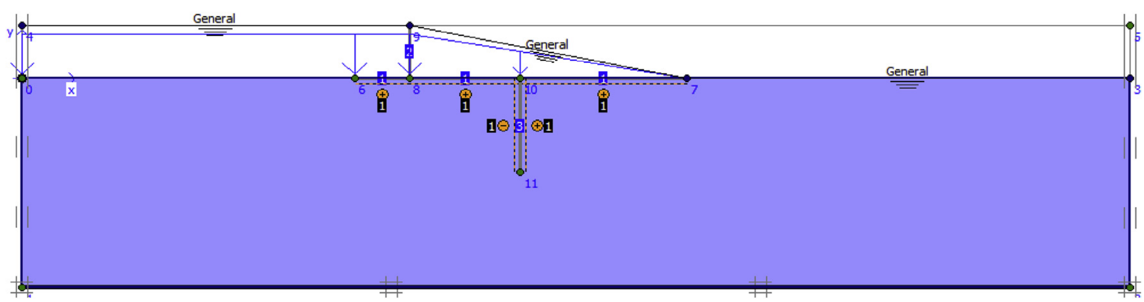


Fig. 4. Numerical model of diversion dam.

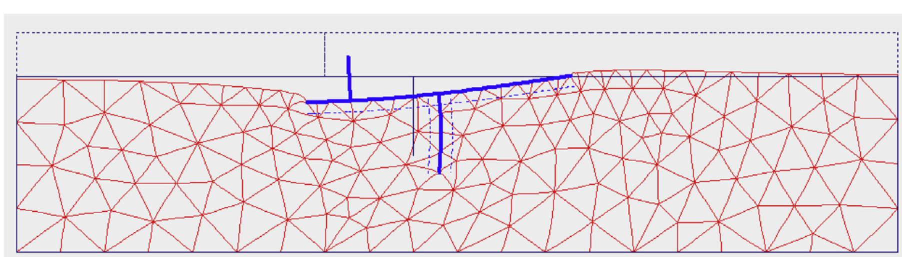


Fig. 5. Deformed mesh of diversion dam.

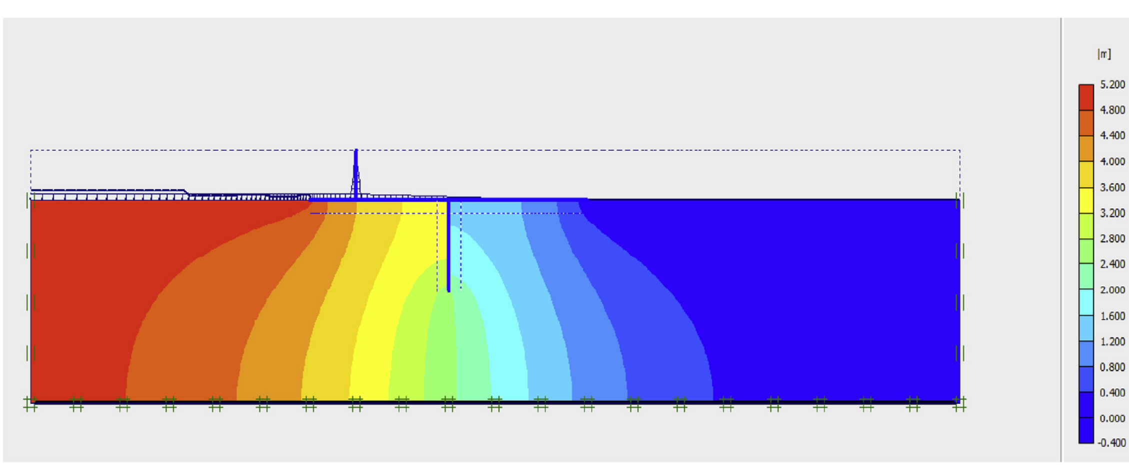


Fig. 6. Ground water head in diversion dam.

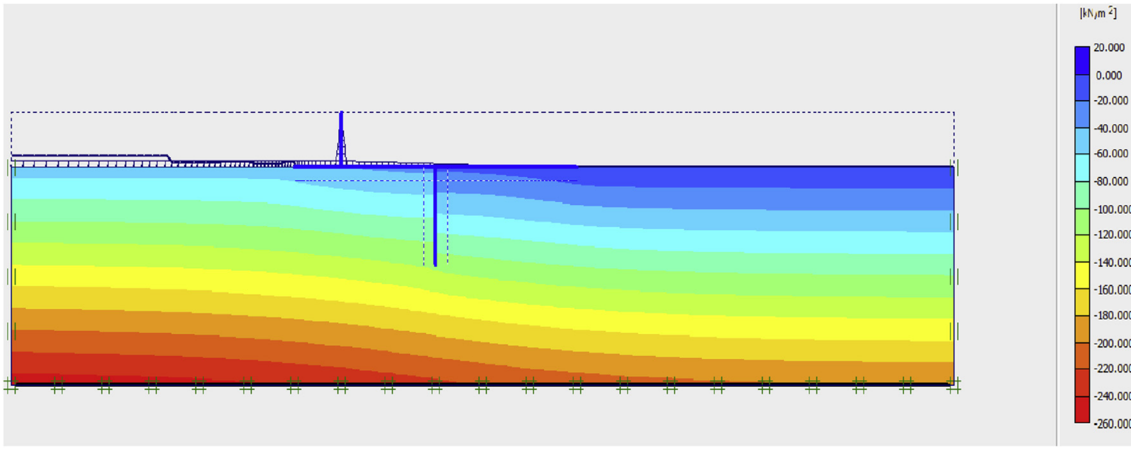


Fig. 7. Pore pressure in diversion dam.

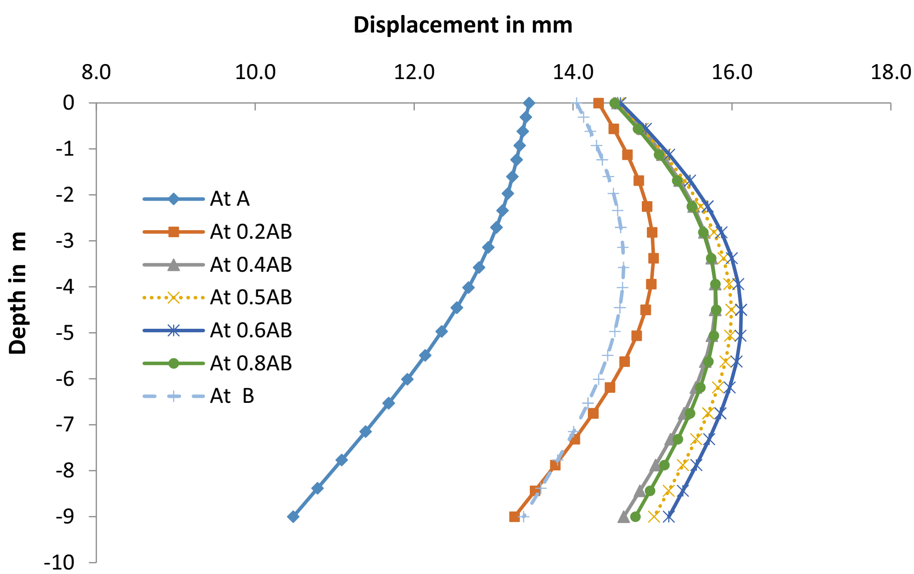


Fig. 8. Displacement of cut off wall for varying locations.

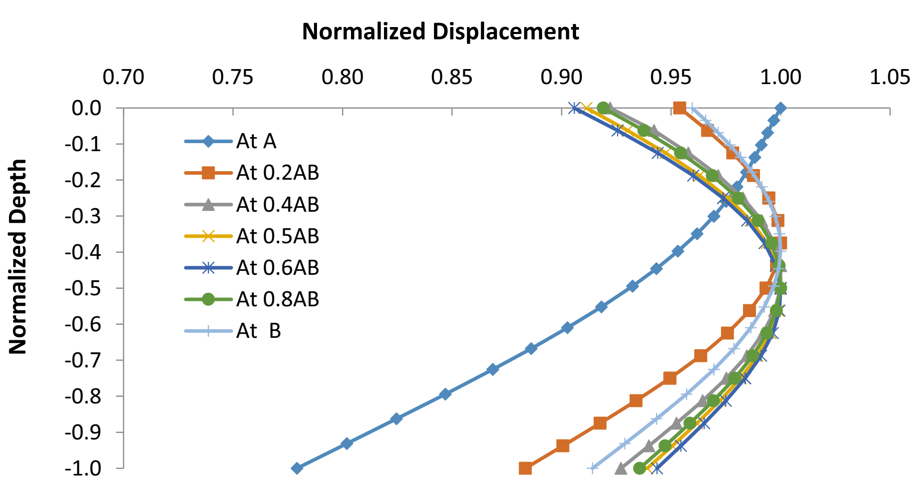


Fig. 9. Normalized displacement of cut off wall for varying locations.

located at end of downstream, the second lowest maximum displacement occurs in the cut off wall.

On shifting cut off wall progressively from upstream end to downstream end, the displacement at top end of the cut off wall increases marginally and attains the maximum value when positioned at location 0.6AB. Beyond that, the displacement at top end reduces gradually. But, on shifting the location of cut off wall from upstream end to downstream end, the displacement at bottom end of the cut off wall increases at rapid

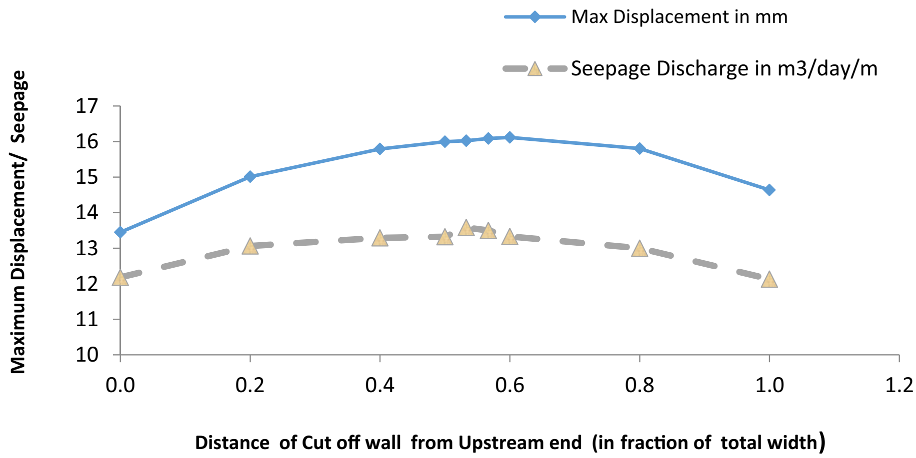


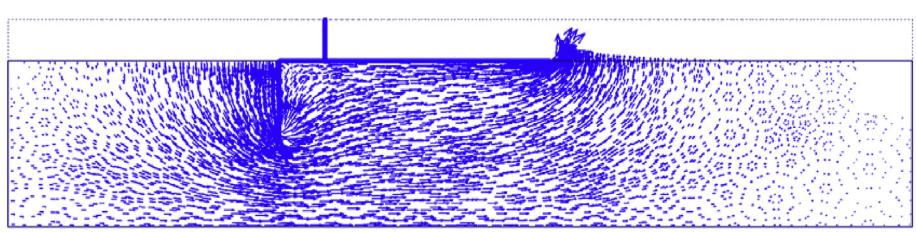
Fig. 10. Maximum displacement and seepage for varying locations.

Table 3
Displacement and Seepage for varying locations.

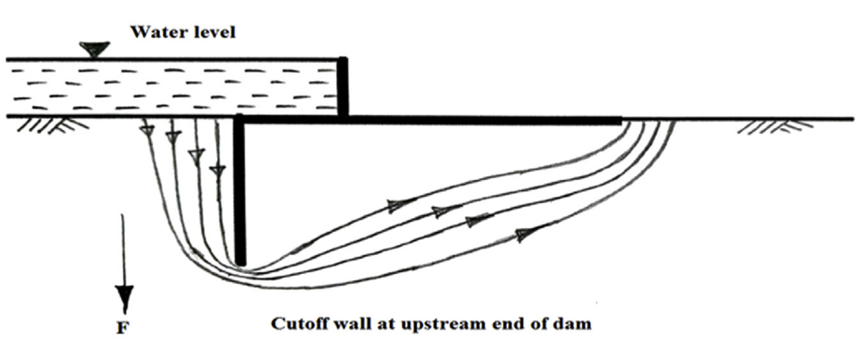
Location of Cut off Wall from Upstream End	At A	At 0.2 AB	At 0.4 AB	At 0.5 AB	At 0.53 AB	At 0.57 AB	At 0.6 AB	At 0.8 AB	At B
Max Displacement in mm	13.45	15.01	15.79	15.99	16.02	16.09	16.12	15.80	14.64
Displacement at top end of wall in mm	13.45	14.32	14.56	14.58	14.55	14.59	14.60	14.52	14.05
Displacement at bottom end of wall in mm	10.48	13.26	14.64	15.02	15.11	15.18	15.21	14.79	13.38
Seepage Discharge in m3/day/m	12.18	13.06	13.29	13.32	13.58	13.50	13.33	13.00	12.13

rate and attain its maximum at 0.6 AB. Beyond that location, the displacement reduces gradually. The magnitude of displacement between top and bottom end for each corresponding locations are compared. It is observed that the bottom end displacement is lesser than the upper end displacement, when the cut off wall is located at or near upstream end. By shifting the cut off wall location towards downstream end, the bottom end displacement increases but top end displacement decreases marginally. On nearing the downstream end, again the top end displacement increases over the bottom end displacement. However, when the cut off wall is located at downstream end, again there, the upper end displacement is more than the bottom end displacement.

The rate of seepage for varying location of cut off wall is obtained from the numerical model and the same is plotted. Fig. 10 shows the maximum displacement and seepage rate obtained for varying location of

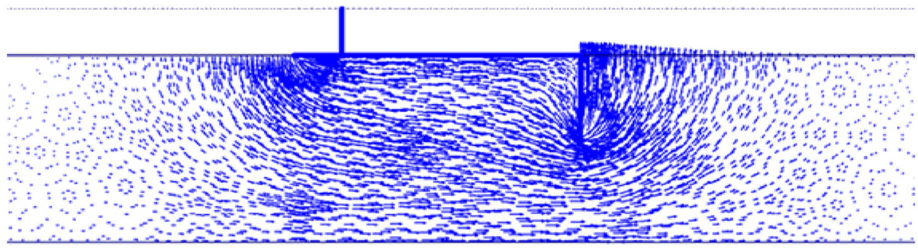


(a)



(b)

Fig. 11. (a) Flow field of cut off wall positioned at upstream end. (b) Simplified flow field of cut off wall positioned at upstream end.



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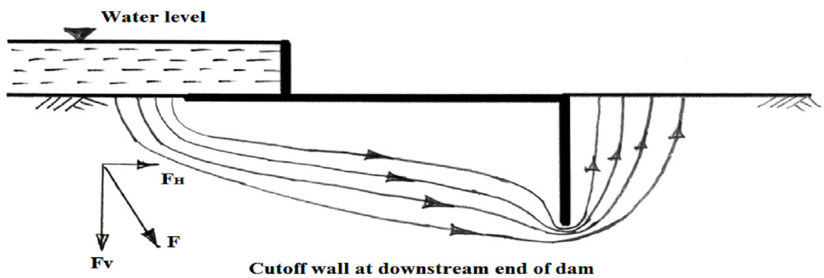
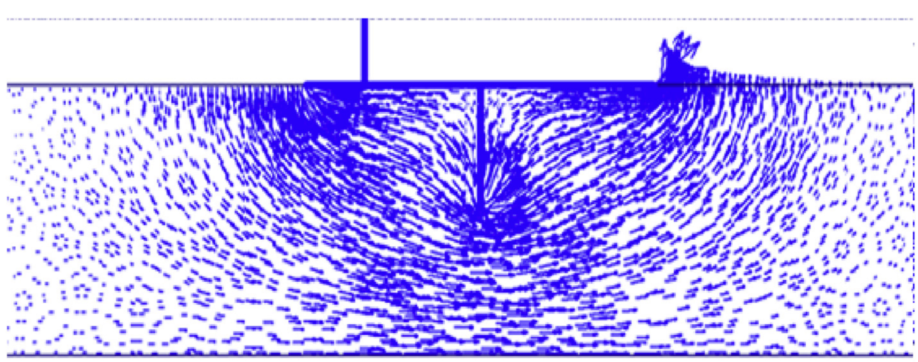


(b)

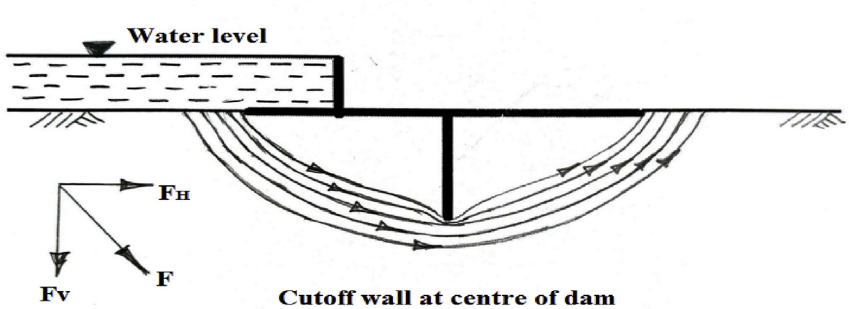
Fig. 12. (a) Flow field of cut off wall positioned at downstream end. (b) Simplified flow field of cut off wall positioned at downstream end.

the cut off wall. Maximum Displacement and Seepage for varying locations presented in Table 3. On comparing the shape of the both maximum displacement curve and the seepage rate curve, it is observed that both curves are similar in pattern. Location of cut off wall for which the seepage is more, there, maximum displacement is also more. Similarly, where the maximum displacement is lower, there seepage rate is also lower. Increase in seepage rate is due to the increase in seepage velocity. So, the relation between the seepage rate and maximum deformation can be analyzed.

According to Mansuri et al [14] and Mansuri and Salmasi [15], the maximum seepage rate occurs when the cut off wall is positioned at center of the dam. The data obtained from this study also shows that, the maximum seepage occur at 0.53AB from the upstream end i.e. almost center of the diversion dam. The pattern of seepage flow varies according



(a)



(b)

Fig. 13. (a) Flow field of cut off wall positioned at center of dam. (b) Simplified flow field - cut off wall positioned at center of dam.

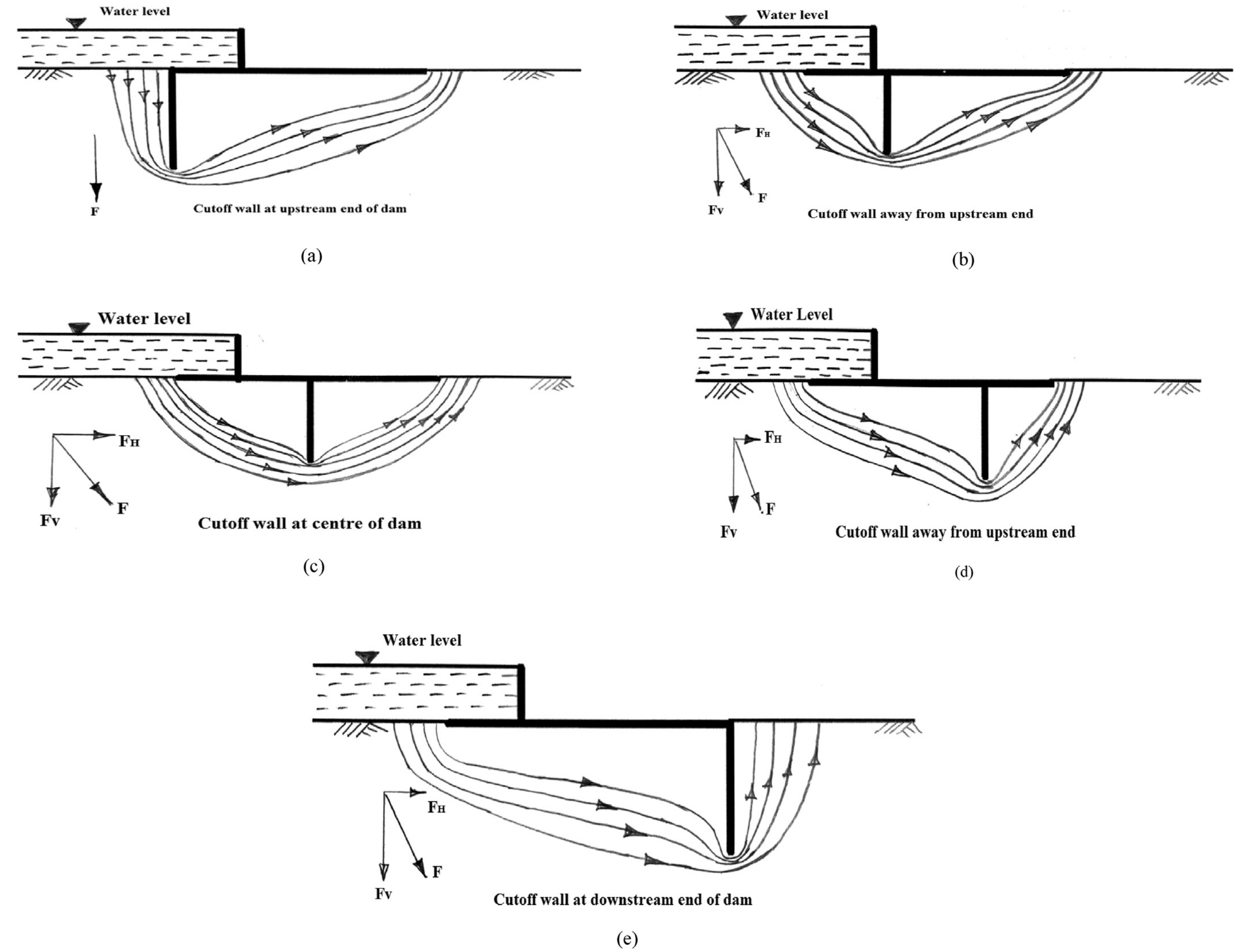


Fig. 14. 14(a), 14(b), 14(c), 14 (d) and 14(e) Seepage force of streamline flow for varying locations.

to the location of cut off wall. When the cut off walls are located at both extreme ends, the seepage streamlines are required to take longer path. However, on moving the cut off wall towards the center of dam, the length of seepage path reduces. At the center of diversion dam, the seepage streamlines require a shortest path. Fig. 11(a) shows the flow field obtained from numerical analysis and Fig. 11(b) shows the simplified flow field for positioning the cut off wall at upstream end.

Fig. 12(a) shows the flow field obtained from numerical analysis and Fig. 12(b) shows the simplified flow field for positioning the cut off wall at downstream end. Fig. 13(a) shows the flow field obtained from numerical analysis and 13(b) shows the simplified flow field for positioning the cut off wall at center of diversion dam. When the streamline is tracing the longer path, the seepage stream loses it velocity due to friction in the soil particles. When the cut off wall is positioned at center of diversion dam, due to shortest path of travel, the frictional loss is less, and hence, the seepage velocity is high. This seepage velocity exerts dynamic force on every point all along the streamline, in the direction tangential to the streamline curve at that point. The seepage rate and the direction of flow, influence the magnitude of seepage force acting on the cut off wall (see Fig. 14).

While the cut off wall is positioned at the end of upstream apron, the direction of seepage flow is downward. This downward flow increases effective vertical stress in the upstream side of the cut off wall. As the flow is downward, the horizontal component of dynamic force exerted on the cut off wall can be taken as nil or very minimum, thus making the net pressure difference between the both faces of cut off wall as a predominant force. Hence, at the upstream end position, the pressure difference on the faces of cut off wall is the predominant force which deform the cut off wall. When the cut off wall is shifted towards downstream end progressively, the flow pattern of streamlines changes accordingly. The downward flow of the seepage lines progressively reorients themselves towards horizontal direction. Therefore, on shifting the location of cut off walls progressively, the horizontal component of seepage force increases and the deformation of cut off wall also increase. The maximum deformation occurs when the cut off wall is positioned at 0.6AB from the upstream end.

Further shifting of cut off wall towards the downstream end, the deformation starts reducing due to change in the flow pattern of the seepage streamline flow. While the cut off wall is positioned at the downstream end of the diversion dam, at the downstream side of the cut off wall, the seepage flow turns upward. As this flow exerts seepage force on the soil particles against the gravity, the weight of soil particles gets reduced partially and consequently, the vertical effective stress on the downstream side of the wall also reduce. This reduced effective vertical stresses increases the pressure difference between the both faces of the cut off wall. Therefore, along with horizontal component of the seepage force, the increased net pressure difference between both faces of cut off wall induces additional deformation in the cut off wall. However, this deformation in the cut off wall is lesser than previous position of cut off walls and it is, however, higher than deformation inflicted when the cut

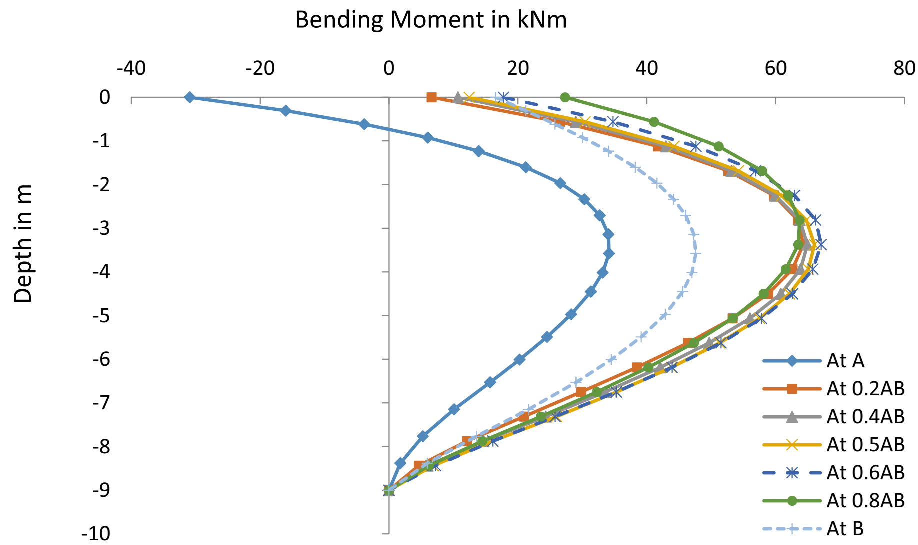


Fig. 15. Bending moments in cut off wall for varying location.

off is positioned at the upstream end. Hence, it is noted that the cut off wall undergoes lowest deformation when the wall is positioned at upstream end, and second lowest deformation when positioned at downstream end. Cut off wall gets its maximum deformation when it is positioned at 0.6AB from the upstream end.

3.2. *Bending moment in the cut off wall*

The bending moment acting on the cut off wall for varying the location under constant differential water head is analyzed. Deformation of cut off for additional locations at 0.1AB, 0.3AB, 0.7AB and 0.9AB also studied. On studying the pattern of bending moment, it is noted that the maximum B.M increases while shifting the cut off wall towards downstream end. The bending moments in cut off wall for varying its location is given in Fig. 15. There is a sudden increase in maximum bending movement while shifting from the upstream end. Then, the gradual increase in bending moment continues up to the location of 0.6AB and then it starts reducing. While shifting the cut off wall to downstream end, there is a sudden decrease in maximum bending moment in the cut off wall. The lowest maximum bending moment is observed when the cut off wall is located at upstream end. The second lowest maximum bending moment is observed while the cut off wall is located at the end of downstream apron. For all other locations between both extreme ends, the maximum bending moment is higher with maximum of maximum BM occurring in the cut off wall at location 0.6AB. However, except at both extreme ends, variation in maximum B.M is very small and gradual. The sudden increase or decreases in maximum BM happen at both extreme ends. The magnitude of maximum bending moment is related with the maximum displacement that occurs for various locations of cut off wall.

The maximum bending moments in cut off wall for varying locations presented in Table 4. The normalized bending moment versus normalized depth is plotted in Fig. 16. Shear force acting on the cut off wall for varying its location is given in Fig. 17. The normalized shear force plot is given in Fig. 18. Pore pressure acting on the cut off wall for varying its location also given in Fig. 19.

The normalized plot of maximum displacement, maximum bending moment and seepage rate with respect to the various location of cut off wall is plotted in Fig. 20. This plot shows that the behavior of seepage rate and maximum displacement are almost similar for varying location of cut off wall. Both are maximum, when the cut off wall is located at center of diversion dam. Based on the pattern of displacement, the maximum Bending Moment occurs.

3.3. *Uplift pressure on the impervious apron*

The location of cut off wall influences the uplift pressure exerted at the bottom of impervious apron or impervious blanket. The measure of uplift pressure is the one of the main parameter which affects the factor of safety of the diversion structure. Numerical study carried out to ascertain the uplift pressure acting on the impervious apron for varying location of cut off wall from upstream end to downstream end. The cut off wall is positioned at 0.0AB, 0.2AB, 0.4AB, 0.5AB, 0.6AB, 0.8AB and 1.0AB from upstream end, where AB is the length of impervious apron or blanket from upstream end to downstream end.

The profile of uplift pressure acting on the impervious apron obtained for various locations of cut off wall and the same is given in Fig. 21. The total uplift pressure acting on the impervious apron is obtained for every location of cut off wall and are plotted in Fig. 22. The total uplift pressure is minimum when the cut off wall is positioned at upstream end of impervious apron. The total uplift pressure is maximum when the cut off is positioned at downstream end of the impervious apron.

The percentage increase in uplift pressure for various location comparing the total uplift pressure acting on the impervious apron AB, when the cut off wall is positioned at the upstream end is given in Fig. 23. It is understood that when the cut off wall is located at middle of apron, the total uplift pressure acting on the apron AB increases more than 21%, while positioning the cut off wall at downstream end, the total uplift

Table 4
Maximum bending moments in cut off wall for varying locations.

Location of Cut off Wall from Upstream End	At A	At 0.2AB	At 0.4AB	At 0.5AB	At 0.53AB	At 0.57AB	At 0.6AB	At 0.8AB	At B
Max Bending Moment in kNm	34.14	64.28	64.93	66.03	66.11	66.61	**67.06**	63.71	47.60

Bold denotes the maximum of Max Bending Moment value.

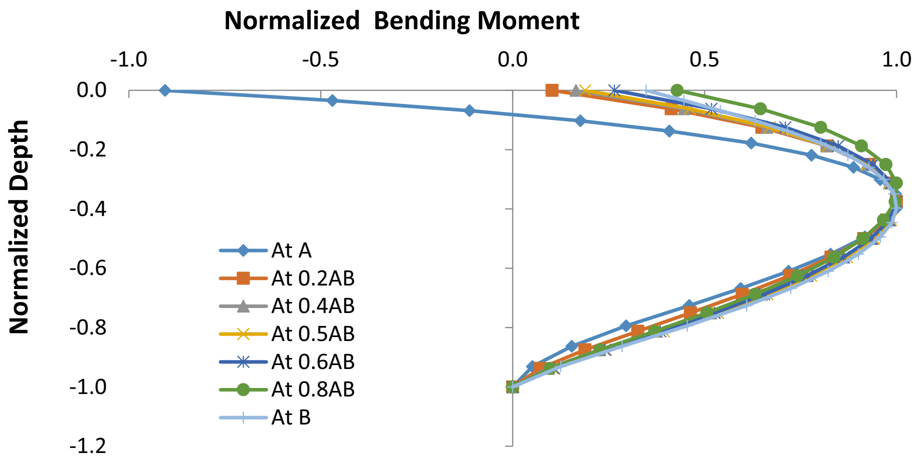


Fig. 16. Normalized Bending moments in cut off wall for varying location.

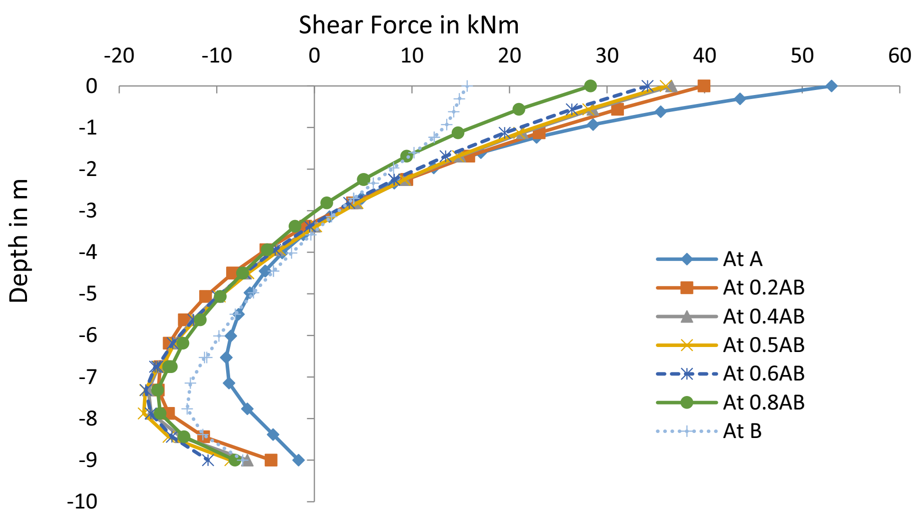


Fig. 17. Shear force acting on cut off wall for varying location.

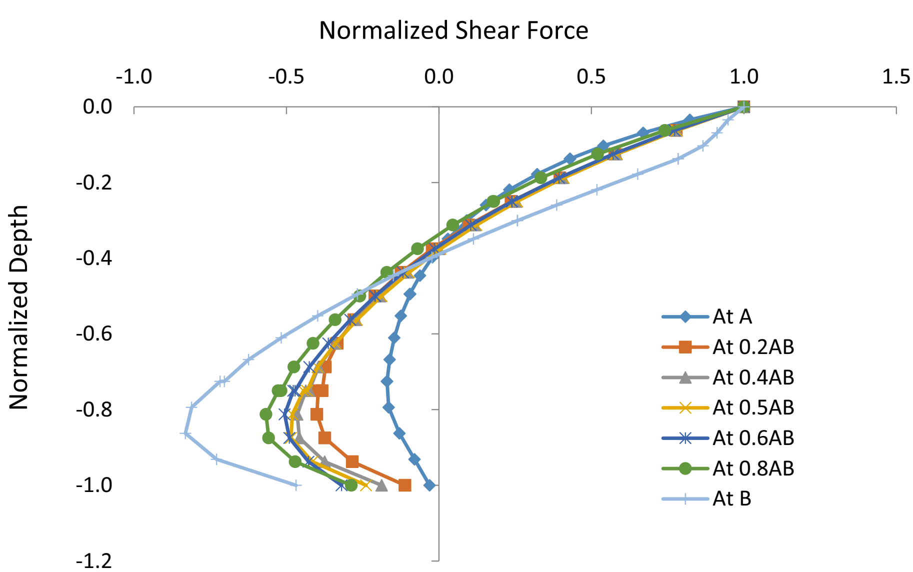


Fig. 18. Normalized Shear force in cut off wall for varying location.

pressure increases more than 67% over the minimum value of uplift pressure.

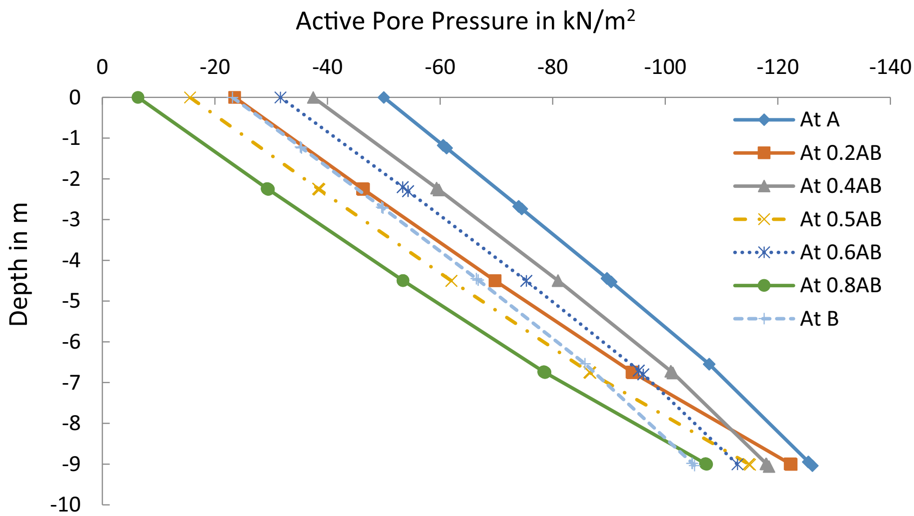


Fig. 19. Pore pressure in cut off wall for varying locations.

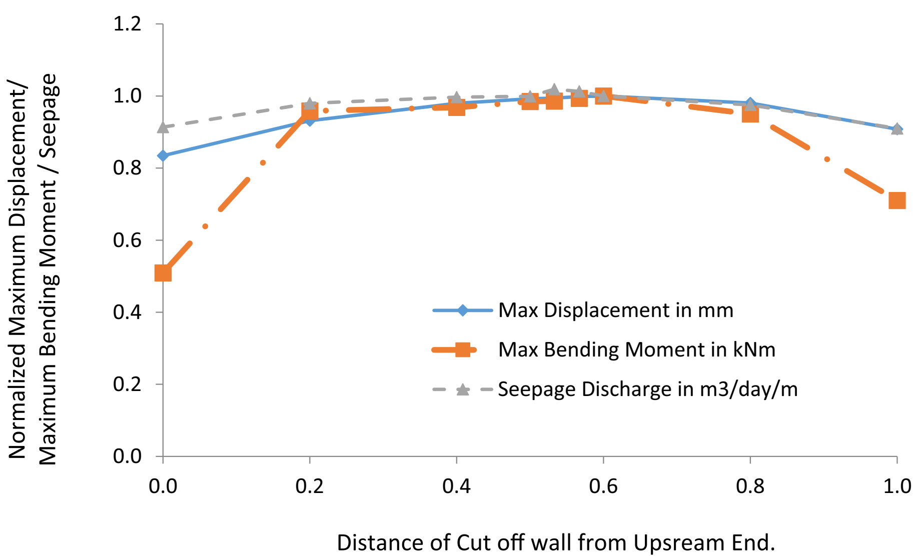


Fig. 20. Normalized plot of maximum displacement, maximum bending moment and seepage rate.

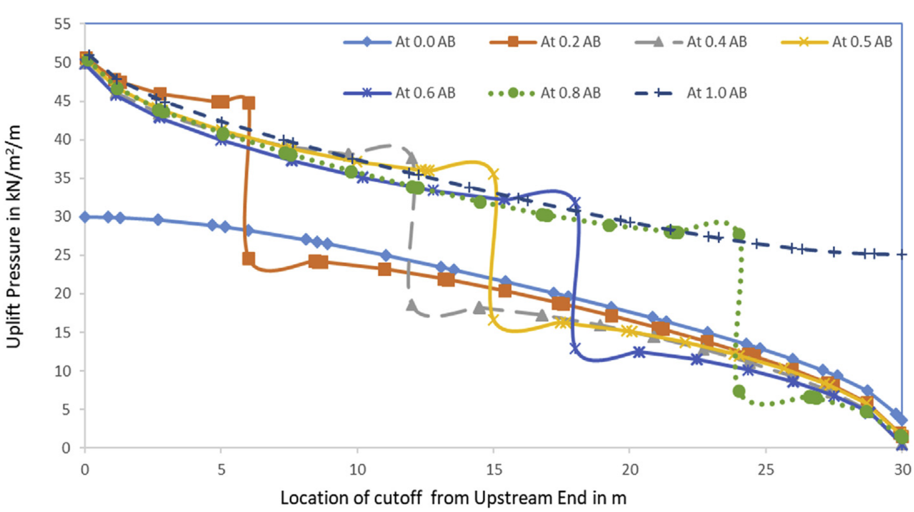


Fig. 21. Uplift pressure for varying location of Cut off wall.

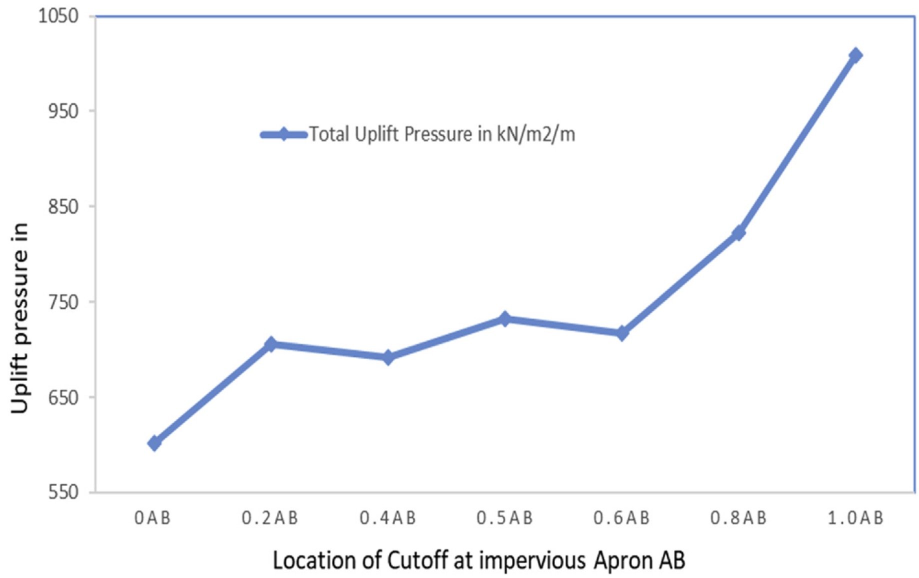


Fig. 22. Total and average uplift pressure for varying location of cut off wall.

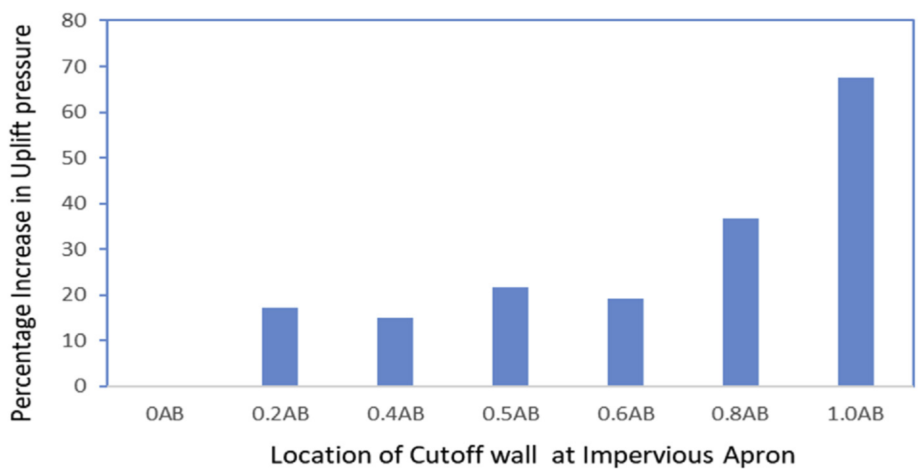


Fig. 23. Percentage increase in uplift pressure for varying locations.

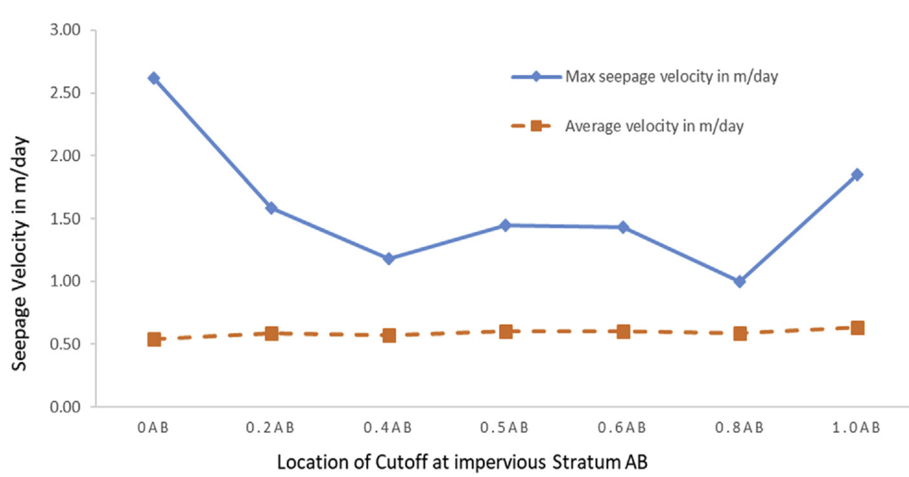


Fig. 24. Average and Maximum seepage velocity for varying location.

3.4. Seepage velocity variations

Numerical study carried out by varying the location of cut off wall from upstream end to downstream end of impervious apron. The cut off wall is positioned at 0.0AB, 0.2AB, 0.4AB, 0.5AB, 0.6AB, 0.8AB and 1.0AB from upstream end, where AB is the length of impervious apron or blanket from upstream end to downstream end. The average seepage velocity and maximum seepage velocity for respective cut off wall positions are obtained. Both values of average seepage velocity and maximum seepage velocity plotted in Fig. 24.

From the plot it can be observed that while the cut off is positioned at the end of upstream, the maximum of maximum seepage velocity is obtained. When the cut off wall is positioned at 0.8AB, the value of maximum seepage velocity is the lowest. The range of variations in average seepage velocity for various location is within 15% (based on the lowest value). But the range of variations in maximum seepage velocity is more than 160% (based on the lowest value).

4. Conclusion

In this numerical study, the location of cut off wall alone is changed, keeping constant, all other soil and structural parameters including applied differential pressure of water head. From upstream to downstream end, pressure gradient decreases due to the frictional losses while passing through soil pores. The active pore pressure difference between the both faces of cut off wall also reduces in general, on shifting the location of cut off wall away from upstream end. However, the deformation of cut off walls increases while shifting the cut off wall from upstream end to 0.6AB and then starts reducing. The deformation of cut off wall positioned at downstream end is higher in magnitude than deformation obtained when positioned at upstream end. Hence, the variation in deformation cannot be due to change in pressure gradient or active pore pressure variation alone. If the changes in pressure gradient and active pore pressure variations are alone the influencing parameters, then the deformation in the cut off wall would decrease on shifting the cut off wall from upstream end to downstream end. However, here it is contrary, means, change in pressure gradient and active pore pressure variations are not the predominant influencing parameters. The effective vertical stress on downstream side of the cut off wall positioned at downstream end reduces. The effective vertical stresses on the upstream side of the cut off wall positioned at upstream end increases, along with the influence by higher-pressure gradient zone prevailing near upstream end. However, these combinations could not influx higher deformation on the cut off wall when positioned at upstream end or downstream end. When the cut off walls positioned at center of the dam, where the vertical effective stresses are not much influenced by the flow of seepage, the deformation is higher.

Take the location of cut off wall just away from the upstream end towards downstream side. Here, there is a sudden increase in deformation comparing the deformation of wall located at upstream end. This is due to increase in seepage force acting on the wall. At upstream end, cut off wall is subjected to nil or very low seepage force due to downward flow of seepage. Just shifting the wall away from upstream end introduces or increases the horizontal component of seepage force on the cut off wall, which is responsible for sudden increase in deformation of cut off wall. These all contemplates that the force exerted by the seepage flow is more predominant than the change in pressure gradient and pore pressure variations in deforming the cut off walls. Therefore, based on above study, the following conclusions can be drawn.

i. The deformation in cut off wall of diversion dam formed in sandy soil is lowest when the cut off walls positioned at upstream end. The cut off wall is subjected to second lowest deformation, when it is positioned at downstream end. The maximum deformation occurs, when the cut off walls positioned at 0.6AB from the upstream end, where AB is the width of diversion dam.
ii. The lowest maximum bending moment occurs, while the cut off is located at upstream end. The second lowest maximum bending moment occurs, when the cut off wall is located at the downstream end. The highest maximum bending moment in the cut off wall occurs when the wall is positioned at 0.6AB from the upstream end, where AB is the width of diversion dam.
iii. The seepage rate in the diversion dam is highest when the cut off wall is positioned at center of the diversion dam. The seepage rate and the maximum displacement traces similar pattern for varying the cut off wall location.
iv. The seepage force is more predominant than the pressure gradient and active pore pressure variations in deforming the cut off walls of diversion dams.
v. The uplift pressure acting on the impervious apron is maximum while the cut off is positioned at the downstream end of apron. When it is located at upstream end impervious apron, the uplift pressure is minimum. The variation of uplift pressure is more than 67% over the minimum value.

Declarations

Author contribution statement

S Sivakumar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

N Almas Begum & PV Premalatha: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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