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Effect of Horizontal Drain Length and Cutoff Wall on Seepage and Uplift Pressure in Heterogeneous Earth Dam with Numerical Simulation

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ORIGINAL ARTICLE

ABSTRACT: Design of earth dams and their problems are important during construction and after it, because of their potential hazards and failure for downstream population. This study focus on the effectiveness of using horizontal drain and cutoff wall in reducing seepage flow from an assumed heterogeneous earth dam. For this purpose various horizontal drain lengths and cutoff wall depth examine under the earth dam in different location of foundation. Seepage analysis, hydraulic gradient and uplift pressure, are computing by numerical simulation, using Seep/w software. Results show that increasing horizontal drain length, cause slightly in increasing seepage rate and increasing hydraulic gradient. Optimum location of cut off wall for reduction of seepage rate and piping is in the middle of dam foundation. By increasing in cut off wall depth, seepage from earth dam and its foundation is reducing. Different location of cut off wall in dam foundation has little effect on exit hydraulic gradient and always it is less than unity. Installation of cut off wall in middle of foundation, results 19.68 percent decreasing in hydraulic gradient respect to existent of cut off wall in upstream of dam.

Keywords: Drain, Exit Gradient, Earth Dam, Seepage, Seep/W

INTRODUCTION

Among the various failures of earth dams, failure resulting from a quick condition, and piping in foundation soils due to high seepage pressures is highly dangerous. If piping is not halted, it may result in a catastrophic collapse of the structure. Seepage through the earth dams and its foundation is controlled by two approaches, which are generally used in combination (Peter 1982). The first approach involves reduction of the quantity of seepage, which may be achieved by providing antiseepage elements of passive protection, e.g., sheet pile (steel, wooden), cutoff wall, slurry trench, clay sealing, upstream impervious blanket, grout curtain, concrete wall, diaphragm wall, etc. The second approach involves providing a safe outlet for seepage water, which still enters the earth dams or the foundation. This may be achieved by providing antiseepage elements of active protection such as filters, drains, sand drains, stone columns, ditches, and relief wells (Sherard et al. 1963; Peter 1982).

About 30% of dams had failed due to the seepage failure, viz piping and sloughing (Middlebrooks 1953). Recent comprehensive reviews by Foster et al. (2000a, b) and Fell et al. (2003) show that internal erosion and piping are the main causes of failure and accidents affecting embankment dams; and the proportion of their failures by piping increased from 43% before 1950 to 54% after 1950. The sloughing of the downstream face of a homogeneous earth dam occurs under the steady-state seepage condition due to the softening and weakening of the soil mass when the top flow line or phreatic line intersects it. Regardless of flatness of the downstream slope and impermeability of soil, the phreatic line intersects the downstream face to a height of roughly one-third the depth of water (Justin et al. 1944). It is usual practice to use a modified homogeneous section in which an internal drainage system in the form of a horizontal blanket drain or a rock toe or a combination of the two is provided. The drainage system keeps the phreatic line well within the body of the dam (Chahar 2004).

Horizontal filtered drainage blankets are widely used for dams of moderate height. Lion Lake dike (6.5 m high), Pishkun dikes (13 m high), Stubblefield dam (14.5 m high), Dickinson dam (15 m high), etc. are examples of small homogeneous dams built by USBR (2003). Also, USBR constructed the 50 m high Vega dam, which is one of the highest with a homogenous section and a horizontal downstream drain. Design criteria of filtered drainage can be found in many references (Terzaghi and Peck 1967; Vaughan and Soares 1982; Sherard et al. 1984 a,b; Sherard and Dunnigan 1985; Honjo and Veneziano 1989; Sharma 1991). Concrete cut off walls are one of main methods of seepage control and are divided to the following categories according to the material type used in construction:

- Slurry trench cut off wall
- Bentonite-cement cut off wall
- Concrete cut off wall
- Plastic concrete cut off wall

The plastic concrete is an appropriate kind of material due to its high deformability (ICOLD, 1985). The cut off wall construction causes an increase in hydraulic head at the upstream and a reduction in

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downstream part of foundation. As a result, the maximum gradient happens in connection zone of the cut off wall and core (Shahbazian Ahari et al. 2000). The maximum gradient should be less than an allowable limit.

In Zoorasna et al. (2008) study, seepage and stress-strain analysis used to investigate the mechanical performance of cut off wall-core connecting systems in earth dams. Karkheh storage dam in Iran was used as the case study and six different connecting systems were modeled. Total flow, maximum hydraulic gradient, shear stress, shear strains and percent of plastic points were determined in connection zone.

Explicit equations have been obtained in the Chahar (2004) work for calculating the downstream slope cover and the length of the downstream horizontal drain in homogeneous isotropic and anisotropic earth dams. Similar equations have also been obtained for maximum downstream slope cover and minimum and maximum effective length of the filtered drainage. These equations are nonlinear and representative graphs have been plotted for them covering all the practical ranges of the dam geometry.

In the present study, different horizontal drain length and cut off wall systems are used to investigate the effect on seepage, uplift pressure and hydraulic gradient in a proposed inhomogeneous earth dam. Cut off location varies from dam heel to dam toe. Numerical simulation carries out using Seep/w software.

MATERIALS AND METHODS

Governing equations

Seepage discharge obeys Darcy's law (Eq. 1):

$$q = -kA(\partial h / \partial l) \qquad (1)$$

Where q is seepage discharge (cubic meters per second), k is hydraulic conductivity coefficient (meter per second), A is the cross sectional area (m^2) and $\partial h / \partial l$ is the flow hydraulic gradient. Poisson's equation is an equation of water flow in porous media which is the generalized form of Laplace well-known equation (Eq. 2):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = q \qquad (2)$$

Where K_x and K_y are the coefficients of hydraulic conductivity in the x and y direction, respectively (meters per second), h is the total head (meters) and q is the discharge flow rate input/output to the soil (cubic meter per second per unit area). Poisson's equation solution is one of the most complex mathematical problems and numerical methods help for solving differential equations and their conversion into a set of algebraic equations. Seep/w is software to solve Poisson's equation by the finite element method.

Numerical simulation

In this study, a heterogeneous earth dam with dimensions shown in Figure 1 is assumed. In boundary condition, water level (total head) in upstream is 38 meter, water level in downstream was assumed 20 meters. Also, the foundation's floor and its right and left walls and the downstream slope of dam shell are impermeable (zero flow). Nodes around the horizontal drain have atmospheric pressure (zero pressure). The upstream and downstream slope shell of dam have inclination 1V:2.5H and the upstream and downstream slope core of dam have inclination 1V:0.25H which is considered as the primary/base model. Seep/w software can automatically generate a well behaved unstructured pattern of quadrilateral and triangular elements. In this study, unstructured pattern of quadrilateral elements used in simulation.

Two dimensional simulation of heterogeneous earth dam have 2597 elements. In Figure 1, heterogeneous earth dam and its foundation model have 225m length and 20 m depth. The simulation showed that the value of seepage discharge and its hydraulic gradients has a little variation with longer and deeper models. This is achieved by several running of models. The hydraulic conductivity of the dam components is described in table1. It should be noted that value of hydraulic conductivity for shell, filter, core and foundation has been chosen based on mean value of real earth dams.

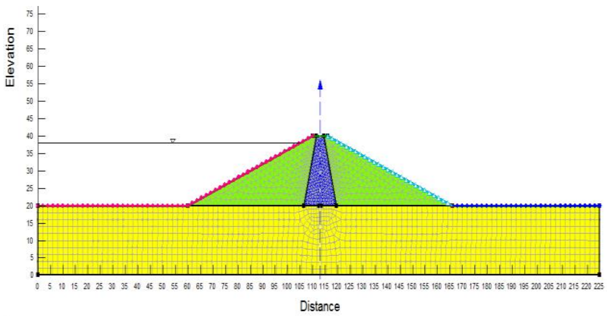

Figure 1. Cross section of heterogeneous earth dam used in this study

Table 1. The permeability of the materials used in the components of the dam

Type of the material	K_{sat} (m/sec)
Shell	0.001
Filter	0.1
Core	0.0000001
Foundation	0.00001

In addition to the numerical simulation of the base model in Figure 1, four other models considered with different horizontal drain length. So that the length ratios of these drain to the downstream shells length in the dam foundation were respectively 0.25, 0.5, 0.75 and 1. For example, the horizontal drains with 23.25m and 46.5m lengths from toe of the dam are shown in Figures 2 and 3, which show 0.5 and 1 length ratio. As seen in Figures 2 and 3, there are smaller elements around the drain or core of dam for more accuracy.

In the next step, we focused on the effects of the cut off in the foundation. The permeability of the cut off materials in the horizontal and vertical directions was selected $1*10^{-9}$ m/sec and its thickness was 1 m. To study the effects of the cut off position on the leakage, exit hydraulic gradient and uplift pressure, we considered the cut off with 7 different placing positions from the dam upstream (heel): 26.7, 46.5, 53, 59.5, 80 and 100 m. Values of the leakage discharge analysis is carry out for a section with 53 m placing position.

In Figures 4 and 5, for example, cut off with 10 m depth is showed where its positions from the dam upstream are 26 and 80 meters.

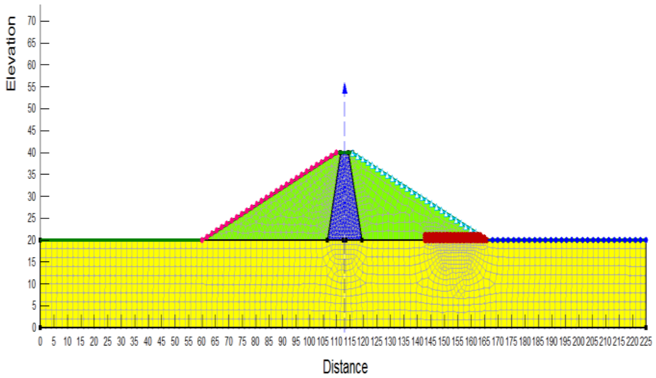

Figure 2. Cross section of earth dam with horizontal drain length of 25.23 meters from the toe of the dam

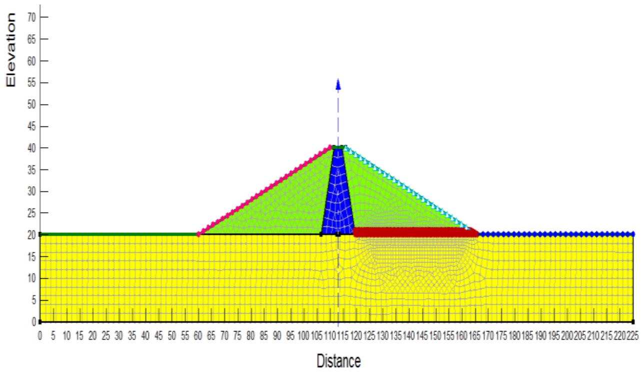

Figure 3. Cross section of earth dam with horizontal drain length of 46.5 meters from toe of the dam

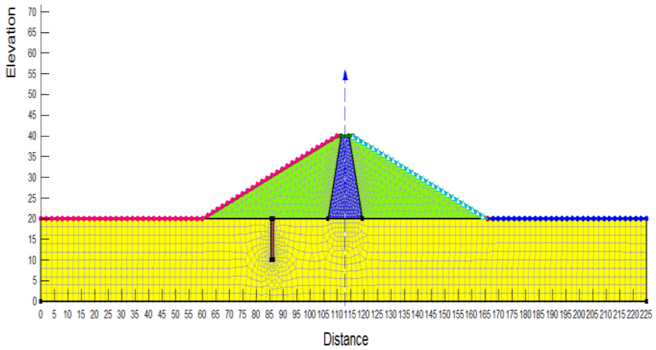

Figure 4. Cross section of earth dam with 10m depth of cut off installation 26 m from upstream (heel) of dam

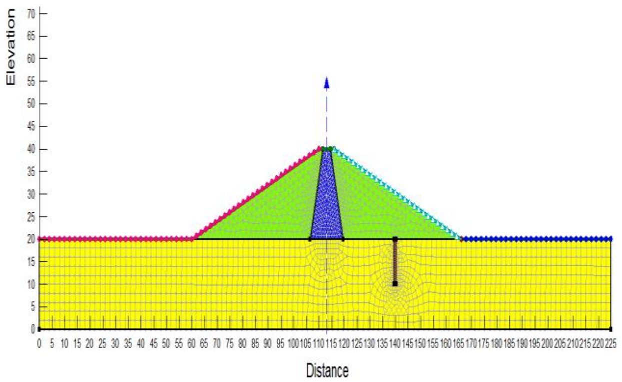

Figure 5. Cross section of earth dam with 10 m depth of cut off installed 80 m from upstream of dam

RESULTS AND DISCUSSION

To study the effects of the horizontal drain length on the seepage changes, exit hydraulic gradient and uplift pressure, four configurations of horizontal drains considered in the toe of the dam with 11.625, 23.25, 34.875 and 46.5 meters length. These lengths introduce horizontal drain ratio equal 0.25, 0.5, 0.75 and 1. In Figure 6, the results of the numerical simulation for the discharge leakage calculation from the dam body and foundation are shown. By the way, in the vertical axis of Figure 6, the increment percent of leakage discharge ratio by using base model is applied.

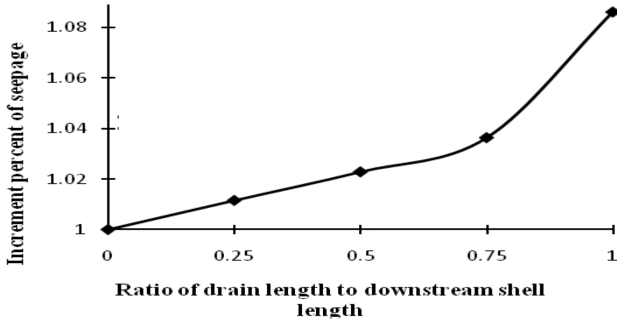

Figure 6. Seepage from earth dam in the different conditions of horizontal drains length

According to Figure 6, when the horizontal drains length increases, the leakage discharge will increase from the body of dam and foundation, too. So that, the value of leakage discharges from the dam body and foundation for the length of horizontal drains will be respectively 11.625, 23.25, 34.87 and 46.5 meters to the base model of 1/15%, 2/28%, 3.63% and 8.6%. The leakage curve gradient became significant in horizontal drain relative length from 0.75 to 1 which shows the more effects of this length on the leakage discharge increasing. It is important to remember though horizontal drain increases the dam leakage discharge, but the existence of drain can prevents the phenomenon of piping. One important point is that more than half of the total leakage discharge takes place in the range of 0.75 to 1 of drain relative length. So if in a project, the leakage amount be important, Figure 6 recommend continuing the horizontal drain with relative length equal to 0.75.
Figure 7 shows an earth dam with a horizontal drain of 34.87 m length after the numerical simulation. In Figure 7, equipotential curves for dam body and its foundation, phreatic line and seepage discharge from the structure, has presented.

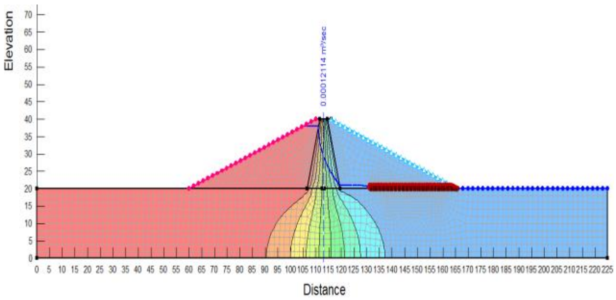

Figure 7. Cross section of earth dam with 34.875 m of horizontal drain from the toe of dam

Diagram of uplift pressure distribution in the dam foundation is presented in Figure 8. The uplift pressure in the contact place of the core with the foundation shows a sharp reduction and the most reduction happens in this location. This is due to low permeability of clay soil in core of dam respect to shell material. Uplift pressure values under the dam core are like Khosla curve. Based on Figure 8, we can conclude that with increase of the horizontal drain length, the uplift pressure of the beneath part of the core decreases.

For better understanding, uplift pressure distribution just about the contact place of the core with the foundation is presented in Figure 9.

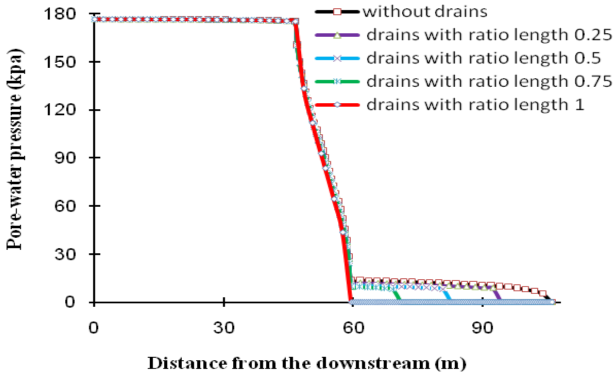

Figure 8. Uplift pressure distribution in the foundation with different horizontal drains length

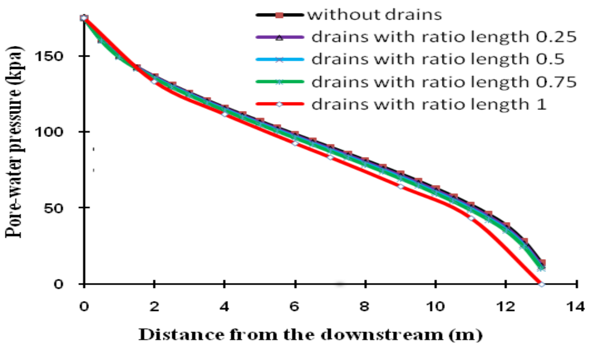

Figure 9. Uplift pressure distribution in under core of dam

In Figure 10, the effect of the horizontal drains length changes on the total forces of uplift pressure is shown. In fact, Figure 10 is produced from sum of area under the curve of Figure 8. It is noted that the increase of the drain length, the total uplift pressure decreases. So that the rate of uplift pressure reduction for the length of the toe drains with 11.62, 23.25, 34.87 and 46.5 meters is respectively 1.62%, 3.19%, 4.54% and 6.03%. It should be noted that in general, uplift pressure is not a danger making element in the earth dam stability. Because, the earth dam upstream and downstream slope cause a big section with high weight which the force of the dam weight is so more than uplift pressure and so is not dangerous.

In Figure 11, the effects of the horizontal drains and its absence in the earth dam toe on the hydraulic gradient are presented. Figure 11 shows that in the horizontal drain locations, the hydraulic gradient growth is happened. But the exit hydraulic gradient is less than the critical gradient (equal to unity) and is not dangerous. Also, the horizontal drain length relative growth causes the exit gradient of the toe increasing and almost gets tangent to 0.5 gradient.

To check the appropriate position of cut off under the dam body, 7 different places were selected in the foundation and conducted the numerical simulation. In Figure 12, the changes of the seepage discharge from the body and the foundation of the earth dam is drawn versus the changes placing positions of the cut off and its depth.

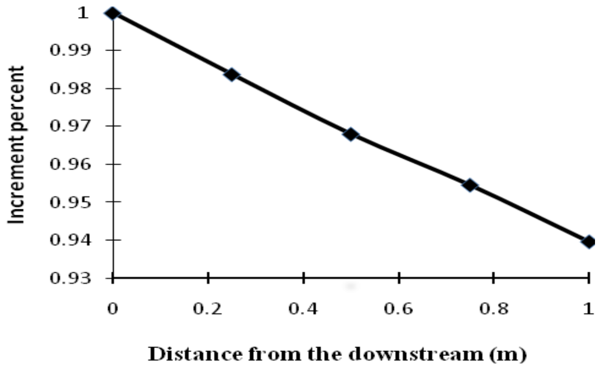

Figure 10. Effects of the horizontal drains length on the total uplift pressure

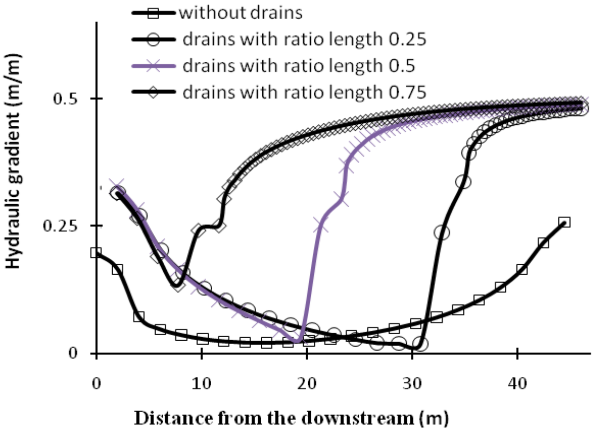

Figure 11. Effects of the horizontal drains length on the changes of the hydraulic gradient

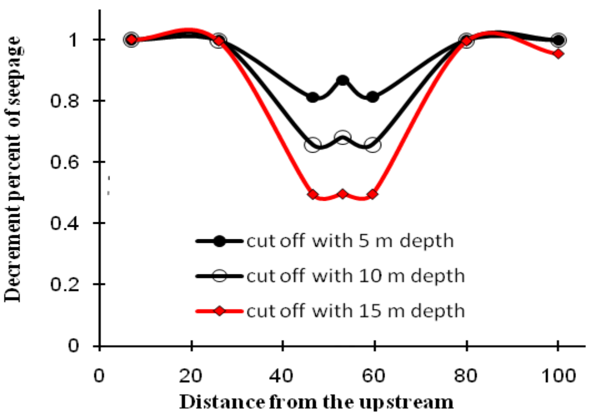

Figure 12. Effects of the cut off position and its depth on the changes of the seepage

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According to Figure 12, when the cut off get near to the middle of the dam foundation, the rate of the seepage discharge from the foundation and dam body suddenly reduces. So, the best place of the cut off is the middle of the foundation of the earth dam for seepage discharge and piping reduction. For a cut off position in 53 meters, the rate of the seepage discharge from the body and the foundation in the depth of 5, 10 and 15*m*, the rate of seepage discharge reduction to the base model is respectively 13.16%, 31.89% and 50.17%. Also according to Figure12, increase of the cut off depth causes the significant reduction of the seepage discharge.

To study the effects of the cut off depth on the changes of the seepage discharge rate, a cut off with 4 depth rates of 5, 10, 15 and 19.9 *m* were considered in the middle of the foundation.

Figure 13 shows that increase of the cut off depth reduces the seepage discharge from the dam body and foundation. For a cut off in the depth of position 53m, the rate of the seepage discharge from the dam body and foundation for the depth of 5, 10, 15 and 19.9 *m* to the base position is respectively 13.16%, 31.89%, 50.17% and 79.77%.

To study the effects of the cut off on the changes of the total value of uplift pressure, a cut off with the depth of 3, 5, 10 and 15 *m* were considered in different positions. Also the severity factor is the ratio of uplift pressure values to the base position total uplift pressure. In Figure14, the effects of the different placing positions of cut off on the uplift pressure are presented.

To study the effects of the cut off all depth on the changes of the total values of uplift pressure, cut off with depth of 4, 5, 10, 15 and 19.9 m in the middle position of the foundation is considered. The results of the uplift pressure values calculation in all positions are shown in the Figures 17 to 19.

Figure 14 shows that the minimum values of uplift pressure in the existence of the cut off at the beginning of the central core from the dam upstream are happened. So, we can conclude that the best place of the cut off in order to uplift pressure reduction is its position in 46.5 meters from the dam upstream. `

For example, a cut off wall with the depth of 10 and 15 meters in the middle of the foundation is considered in Figures 15 and 16. Also in Figures 15 and 16, equipotential curves and the seepage phreatic line can be seen.

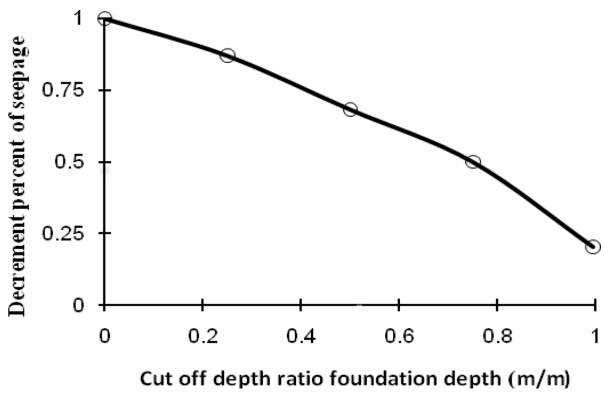

Figure 13. Effects of the cut off depth on the seepage

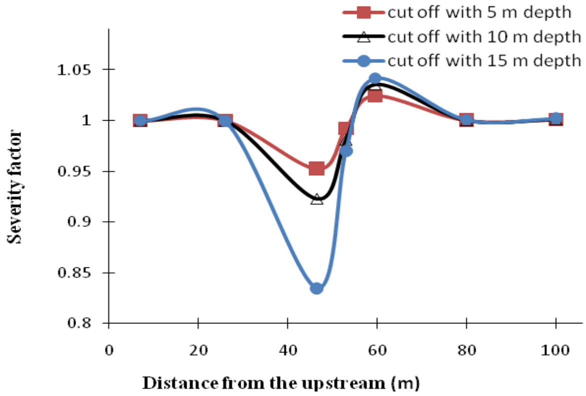

Figure 14. Effects of cut off position on the changes of the total values of the uplift pressure

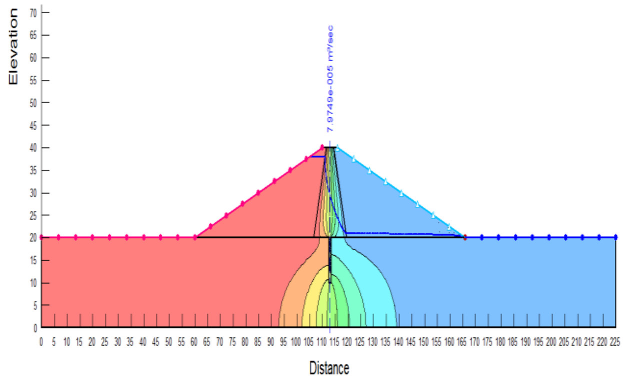

Figure 15. Cross section of an earth dam with 10 m depth of cut off and 53 meters from the upstream

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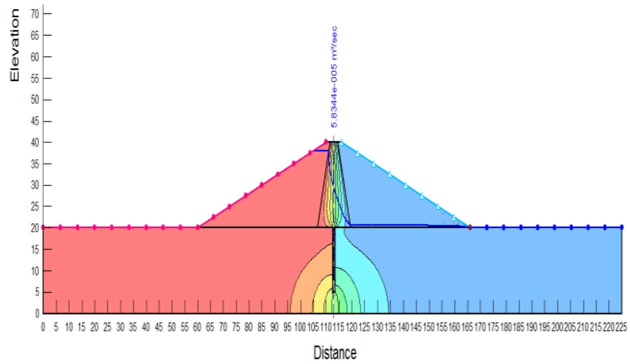

Figure 16. Cross section of an earth dam with 15 m depth of cut off and 53 meters from the upstream

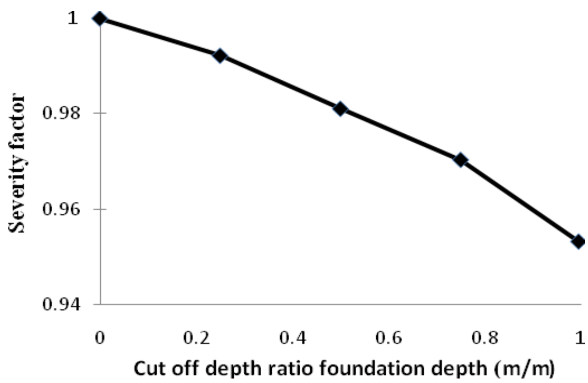

Figure 17. Effects of the cut off length on the changes of the total uplift pressure

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Figure 17 shows that increase of the cut off depth reduces the total values of uplift pressure. A cut off in the position of 53m from the dam upstream the seepage discharge rate for the depth of 5, 10, 15 and 19.9 m the reduction rate of uplift pressure values to the base position, respectively is 0.78%, 1.9%, 2.97% and 4.19%.

The effect of cut off depth on the uplift pressure distribution under the earth dam and under the core respectively is presented in the diagrams 18 and 19. Regarding them, the changes of the uplift pressure values under the shell is low due to the more permeability of the shell to the core. The core low permeability causes the happening of the most water potential reduction. Regarding Figure 19, the increase of the cut off depth under the core causes the increase of the uplift pressure in the upstream of the cut off and reduction of the uplift pressure in the wall downstream.

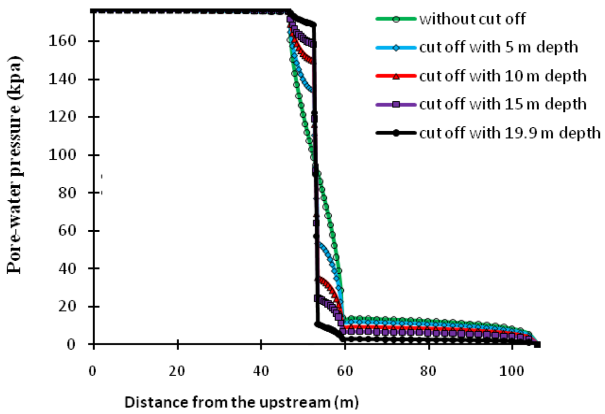

Figure 18. Effects of the cut off length on the uplift pressure distribution

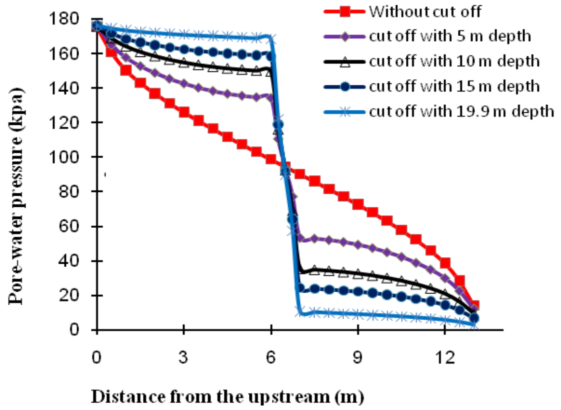

Figure 19. Effects of the cut off length on the uplift pressure distribution

To study the effects of the cut off position on the exit hydraulic gradient, cut off in the depth of 5 meters with 7 different places of 7, 26, 46.5, 53, 80.5, 59 and 100 m were considered from the dam upstream in Figure 20. Also the exit hydraulic gradient for the toe is considered with 18 meters from the dam downstream.

Figure 20 shows that with the movement of the cut off to the middle of the foundation, there will be the reduction of the exit hydraulic gradient. The existence of the cut off in the middle of the foundation comparing to its position in the upstream, causes 19.68% reduction of the exit hydraulic gradient in the toe. A cut off in the 100m of the dam upstream causes the low increase of the exit hydraulic gradient due to the being in the evaluation position of the dam toe. In general, the placing position of the cut off in the dam length has no significant effects on the exit gradient changes and always is less than 1.

In Figure 21, to study the effects of the cut off depth on the exit gradient changes values, the cut off with 4 depths of 5, 10, 15 and 19.9 m in the middle part of the dam is considered.

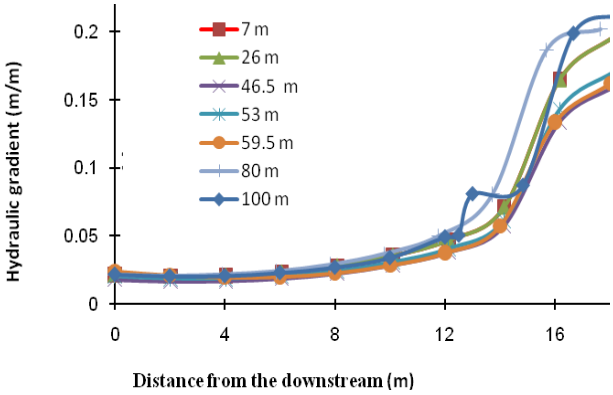

Figure 20. Effect of the cut off with 5m depth on the exit hydraulic gradient changes

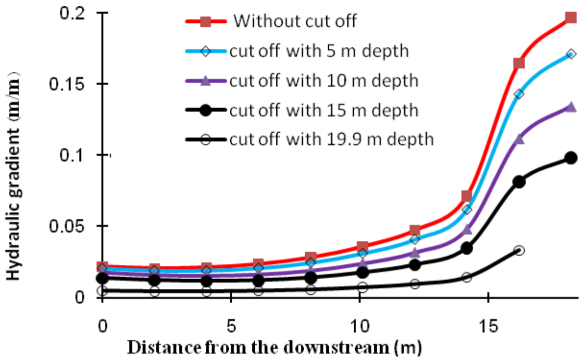

Figure 21. Effects of the cut off depth on the toe exit hydraulic gradient

Figure 21 shows that with increase of the cut off depth, the exit hydraulic gradient values reduce. The exit hydraulic gradient changes forms from the toe are influenced by the cut off depth is almost the same with the form of seepage discharge changes. For the cut off in the middle position of the foundation, the exit hydraulic gradient values for the most tolerant point regarding piping for the depths of 5, 10, 15 and 19.9 m the reduction rate of the exit hydraulic gradient ratios to the base position respectively is 31.07%, 31.75%, 50.01% and 83.13%.

Because the values of the exit hydraulic gradient to the critical exit gradient values are low, we can conclude that the existence of the cut off is an appropriate solution for the hydraulic gradient reduction and piping happening in the dam.

CONCLUSION

With increase of the horizontal drains length, the seepage discharge increases, but it reduces piping danger. With increase of the horizontal drains length, the values of the total uplift pressure forces reduce. The changes of the horizontal drain length have no significant affects on the uplift pressure values under the core. With increase of the horizontal drains length, the exit hydraulic gradient of the toe increases, too. The best place for the cut off to reduce the seepage discharge and piping danger is in the middle of the foundation. With increase depth of the cut off, the value of the seepage discharge from the foundation and body reduces suddenly. When there is a cut off in 46.5m of the dam upstream, the uplift pressure values suddenly reduce. With the increase of the cut off, the totals uplift pressure values reduce. With increase of the cut off depth under the core, the uplift pressure increases in the cut off upstream and it reduces in the cut off downstream. The placing position of the cut off in the dam length has no significant effect on the exit hydraulic gradient changes and always is less than 1. With increase of the cut off depth, the exit hydraulic gradient reduces.

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