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Analyzing the Effect of Defect in the Upstream Impervious Blanket on the Seepage Behavior of Earthfill Dam

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Abstract

This paper aims to thoroughly investigate the effect of weakness in the upstream impervious blanket of earthfill dam on the seepage behavior. For this end, a limited zone with high permeability is considered in various situations of impervious blanket. Then, for each situation, the discharge value and seepage pattern through the foundation is determined by performing 2D finite element seepage analysis via GeoStudio software.

Regarding to the analysis result, the location defected zone in upstream impervious blanket directly influences the seepage pattern through dam body and foundation. If the defected zone is occurred in the situations close to the dam core, escaping water from weakness zone of impervious blanket impact the clay core water tightening performance and water potential head drop is not completely occurred in clay core.

From the erosion potential view, the critical condition is directly depended on the foundation permeability. For most permeable foundation, the gradient of 5.6 is recorded for the defected zone located out of dam body in defected zone. For this type of dam, the gradient in foundation is insignificant. If the foundation has lower permeability and defected zone is occurred in impervious blanket next to clay core connection point, the foundation beneath the defected zone is susceptible to erosion.

Keywords: Defected zone, Seepage analysis, Upstream blanket, Earthfill dam.

1. INTRODUCTION

In all dam types, controlling and minimizing the discharge through dam foundation is emphasized by all dam designing bulletins and authorities [1]. One method for water tightening the foundation in the earthfill dams is the covering the upstream ground of reservoir bottom by means of an impervious blanket. The upstream impervious blanket is generally comprised of the materials with low permeability such as compacted clay soil, geomembrane and the asphalt material and applied in such cases where the ground surface has the relatively flat topography and the impervious strata of foundation is relatively located in deeper depth [2, 3, 4].

Regarding to the vital role of water barrier system of foundation in dam safety, any defect can avoid the appropriate functioning the barrier system and may lead to unfortunate consequents. Because the upstream impervious blanket is exposed at the ground surface, this type of water barrier system is fairly more susceptible to damage during operation phase [5, 6]. Besides, the defects in upstream blanket may be developed due to some weakness and shortages during the construction stage. If the clay blanket is compacted with the compaction degree lower than the minimum requirements or the unqualified or low quality material is used for the blanket material, the impervious blanket may be cracked and some weakness could be existed in a blanket. Also, if the clay material of blanket contains the soluble beds like the gypsum, the consequent dissolution of gypsum may lead to create some cavity within blanket and prepare some path for water flow [7].

In all of the instances mentioned above, the upstream impervious blanket is susceptible to impose a weakness in hydraulic barrier functioning. In other words, due to the aforementioned factors, some zones are developed within blanket which have the higher permeability rather than the original blanket material. These higher permeable zones provide short paths for concentrated flow of water from the dam reservoir into the foundation. Thus, even though upstream blanket is properly designed and constructed with adequate length to reduce the seepage, the defected zones in blanket causes for an unexpected increase in the discharge volume through dam foundation. The concentrated seepage through the defected zones is accompanying with a higher gradient leading to erosion in blanket material around the defected zone. Thus, by continuing the concentrated seepage, the dimension of defected zone is progressively increased and seepage magnitude is gradually enhanced [8, 9].

Even though the importance of defect in the water tightening system and preventing methods are thoroughly addressed in many dam design guidelines [1, 2], the hydraulic performance of defected zone and the effect geometry and situation of on the seepage behaviour have not been studied. Thus, this paper aims to thoroughly investigate the effect of weakness on the seepage behavior of the upstream blanket of an earthfill dam. For this end, a limited zone with higher permeability is considered as the representation of defected zone in various situation within upstream impervious blanket. Then, for each situation, the seepage through dam foundation is modelled by performing 2D finite element seepage analysis and compared with intact blanket.

2. NUMERICAL MODELLING

The seepage through the dam body and foundation are modeled in Geostudio software in the form of the two dimensional finite element seepage analysis. This software is a powerful means for analyzing the saturated and unsaturated flow in porous media and widely used in seepage analysis of dams [10].

The numerical model consists of a zoned earthfill dam located on the one-layer alluvial foundation. The dam body includes the clay core, shell and upstream impervious blanket. The slopes of dam face and clay core are 1V:2.5 H and 4V:1H, respectively. Three values of 20, 40 and 60 meters are selected for dam height. The depth of dam foundation is supposed equal to dam height. Besides, three various conditions are considered for foundation permeability. The upstream impervious blanket is comprised of compacted clay material which is connected to the clay core and extended toward the upstream of reservoir ground. The thickness of upstream blanket is 1 meter. For each dam with a specific height, several lengths are considered for impervious blanket and then the optimum length of impervious blanket is determined by numerical analysis in such a way that by increasing the impervious blanket more than the optimum length, seepage through foundation becomes almost constant.

For thoroughly investigating the effect of weakness in upstream blanket, a defected zone with constant width is considered in various situations along the upstream impervious blanket and in each situation; the total discharge through the foundation is determined. The *X* parameter is represented for situation of defected zone in blanket which is defined as the distance of defected zone from the connection point between impervious blanket and clay core. Moreover, for studying the dimension effect of defected zone, three values of 2, 4 and 10 meters are assigned for width of defected zone.

For the boundary condition, the hydraulic head equal to reservoir elevation is assigned to upstream face of dam and top surface of upstream blanket. All nodes on the downstream face of the ground have the zero water pressure head. The lower bound and sides of numerical model are closed with the zero flux boundary condition. All analyses are conducted as the steady state 2-D seepage analysis in Geostudio. The finite element meshing theme of numerical model is shown in Figure 1. The permeability of materials of dam body, foundation and intact upstream blanket and defaced zone of blanket is presented in Table 1. It is supposed that permeability of defected zone of blanket is almost 1000 times greater than the intact condition.

Table 1. The permeability of materials in numerical model

Material name	Clay core	Shell	Foundation	Intact upstream impervious blanket	Defected zone in upstream blanket
Permeability (m/s)	10^{-8}	10^{-3}	10^{-2}, 10^{-4}, 10^{-6}	10^{-8}	10^{-3}

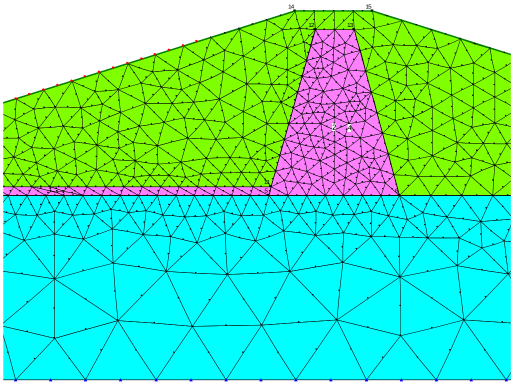

Figure 1. The finite element meshing of numerical model

3. NUMERICAL ANALYSIS RESULTS

For comparison of impervious blanket performance in both intact and defected conditions, the result of seepage analysis, including the phreatic line, equipotential lines and the flow directions are presented in Figure 2. The defected zone with width of w=2 m is located in three different locations of 1) next to clay core connection point (X=0), 2) inside the dam body (X=40 m) and outside of dam body (X=60 m). When weakness of impervious blanket is occurred next to the central clay core, some of water in dam body is flowed throughout the weakness area. In this condition, the weakness in upstream blanket impacts the water tightening performance of clay core. As seen, the whole of water energy drop is not dissipated in clay core and some of potential drop lines of water are established in dam shell and water flow vectors are concentrated toward weakness zone. Thus, the phreatic line in dam shell is not horizontal in equilibrium with reservoir and has a slight slope indicating drop of water energy and flowing in dam shell.

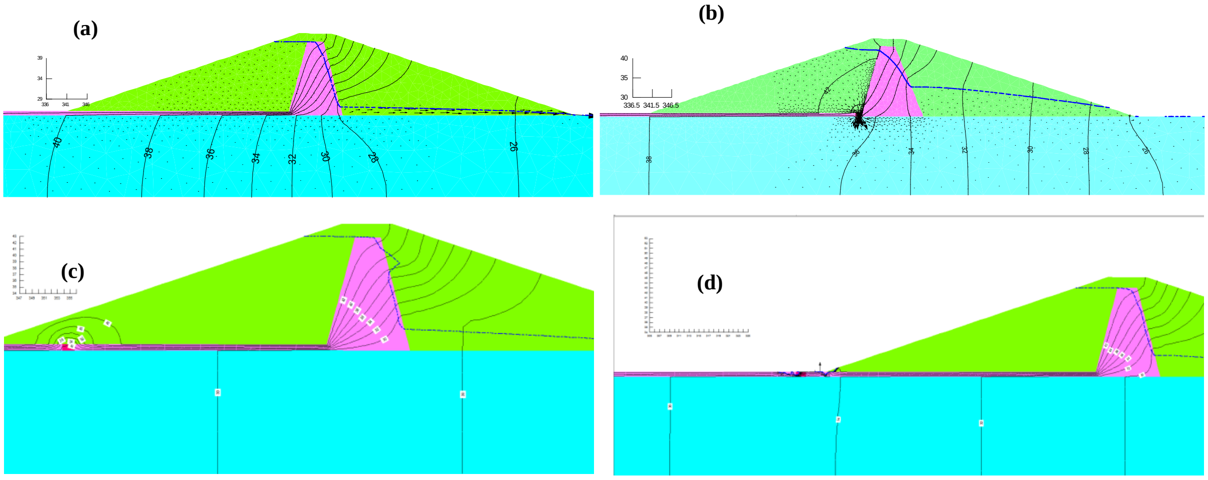

Figure 2. The flow pattern from seepage analysis of dam with height of 20m and foundation permeability of K=10^{-4} m/s: a) intact impervious blanket, b) defected zone next to clay core connection point (X=0), c) defected zone inside the dam body (X=40 m), d) defected zone outside of dam body (X=60 m)

By increasing the distance of defected zone from clay core, the distribution intensity in water tightening performance of clay core is reduced and water is directly entered from dam shell to the foundation throughout the defected zone without any distribution in potential headlines in clay core. However, for a cases that defected zone is located inside the dam body, the drop of water head is found in dam shell and around the weakness zone which causes to establish a gradient force in an area around the weakness zone. This extra gradient may lead to erode the fine grained soil of blanket and will be discussed in later section.

By further increasing in distance of the weakness area in such a way that weakness zone is located outside of dam body (Figure 2-d), the effect of impervious blanket defect on the hydraulic performance of dam body is minimized and only the water is flowed toward the foundation. However, because of far distance of weakness zone, the resultant gradient of water flow in foundation is consequently low and the pattern of water potential head line drop in foundation is similar with the latter locations of weakness zone.

4. SENSITIVITY ANALYSIS

In this section, some sensitivity analyses are conducted to investigate the effect of defected zone in various conditions and determine which situation is the critical for defected zone of impervious blanket. Thus, in each sensitivity analysis, the specific conditions are supposed for dam body and foundation and then, seepage discharge through foundation is determined for various locations of defected zone along the impervious blanket. Then, the foundation seepage ratio parameter is defined as the ratio of the foundation seepage flux in defected condition to the intact condition of impervious blanket. By analyzing the graph of foundation seepage ratio versus defected zone distance from clay core connection point (X), the critical location of weakness zone in each sensitivity analysis is determined.

4.1. EFFECT OF DAM HEIGHT

The graph of foundation seepage ratio versus defected zone position (*X*) for three dams with heights of 20, 30 and 45 m is presented in Figure 3. In this sensitivity analysis, it is supposed that defected zone in upstream blanket is occurred with the width of 2 m and the foundation permeability is 1^{-4} m/s. Regarding to the results, imposing weakness and establishing defected zone in water tightening system causes to increase the flux through dam foundation in the order of 2.3 times greater than the regular condition. For all types of dams, the critical position of defected zone is occurred in situation of X=0 (adjacent to the connection point between clay core and upstream blanket) and by increasing the distance of defected zone from clay core, the effect of weakness in general performance of water barrier system is decreased. For extreme position of defected zone, the foundation seepage ratio approaches to 1 indicating that existing or not existing weakness zone in far way distance does not significantly influence the performance of impervious blanket.

The effect of the dam height on the defected zone performance can be investigated from two distinguished aspects. For situations that the defected zone is located inside the dam body, the traveling path of water from upstream slope face to the defected zone inside the dam body is somewhat short in dam with small height in comparison to the dam with greater height. Thus, because of comparatively greater gradient, more water escapes throughout the defected zone in smaller dam and therefore, for near distance of defected zone position, the foundation seepage ratio is maximum in dam with H=20 m. In contrast, when the defected zone is occurred outside of dam body, water is directly entered from reservoir into the foundation throughout the defected zone. For this condition, increasing the dam height directly increase the seepage flux through the defected zone and hence, for far distance of defected zone, the greatest values of foundation seepage ratio is occurred in highest dam (i.e. H=45 m).

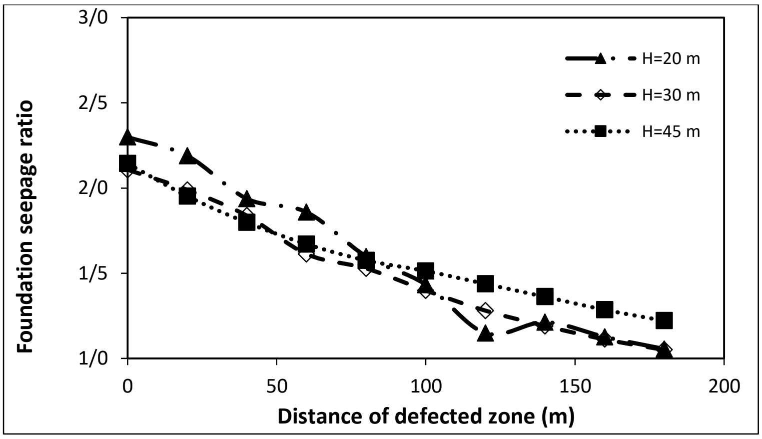

Figure 3. The graph of foundation seepage ratio versus defected zone location (X) in dams with different height (H) and foundation permeability of 1^{-6} m/s

4.2. EFFECT OF DEFECTED ZONE WIDTH

The variation of foundations seepage ratio versus defect location is determined by considering three different opening widths of 2, 4 and 10 m for defected zone and the graph is sketched in Figure 4 for dam with foundation permeability of 10^{-6} m/s and height of 20 m. Also, the foundations seepage ratio graph for dam with similar condition but different foundation with higher permeability is shown in Figure 5. As seen, when the foundation is low permeable, the dimension of weakness in water barrier system has no significant effect in enhancing the foundation seepage discharge and all three graphs of different weakness zone width are coincident. In other words, if foundation has lower permeability, the growing the defected zone may not be main concern and increasing the weakness dimension has no prominent role on enhancing the water escaping through defected zone. However, when the foundation has higher permeability and stopping the foundation seepage is directly depended on the water barrier system performance, growing the weakness dimension straightly increases the water escape throughout the defected zone and at particular location far from dam body, increasing the defected zone width significantly causes to increase the foundation seepage ratio. It should be noted that in higher permeable foundation, when the defected zone of upstream blanket is established in close distances and inside the dam body, the defected zone width has less influence on the foundation seepage ratio and all three graph are coincident for close locations of defected zone.

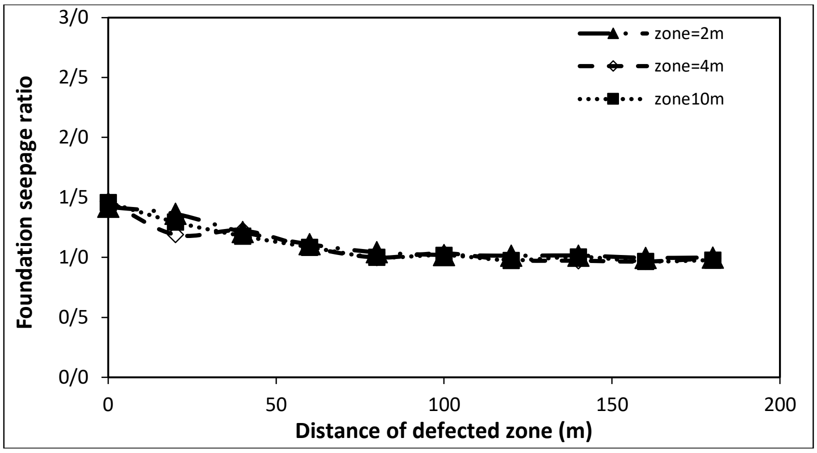

Figure 4. The graph of foundation seepage ratio versus defected zone location (X); the dam has height (H) of 20 m and foundation with permeability of 1^{-2} m/s and different width of defected zone in upstream blanket

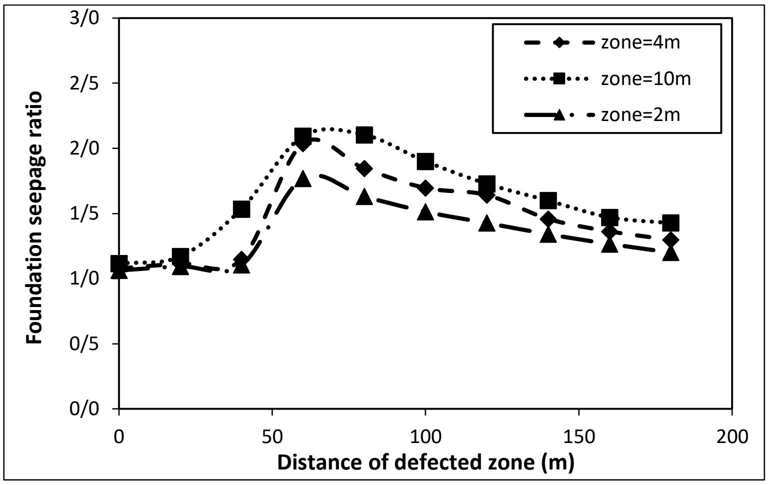

Figure 5. The graph of foundation seepage ratio versus defected zone location (X); the dam has height (H) of 20 m and foundation with permeability of 1^{-2} m/s and different width of defected zone in upstream blanket

5. CRITICAL GRADIENT IN DEFECTED BLANKET

In order to assess the erosion potential due to gradient forces, the maximum hydraulic gradient within defected zone is determined from numerical analysis and compared for different conditions. In dam with height of 20 m, the defected zone is situated in four locations of L1 to L4 (Figure 6). Then, for each situation of defected zone, the maximum hydraulic gradient within both defected zone and foundation beneath the defect is determined and presented in Table 2 and 3, respectively.

From view aspect of erosion, the critical condition is occurred in foundation with highest permeability where the great gradient is established within the defect zone. As compared the gradient in various locations of defected zone in dam with the foundation permeability of $K=10^{-2}$ m/s, it is recognized that by increasing the distance of defected zone from dam core, gradient is increased within the defected zone and when the defected zone is located outside the dam body (i.e. case of No. 4), the resultant gradient exceed unity and reaches the value of 5.6. In other hand, for other situations of defected zone inside the dam body, the gradient is lower than the unity. This consequent confirms with the trend of foundation seepage ratio graph for most permeable foundation. As mentioned in earlier sections, when foundation has the greatest permeability, the maximum value of foundation seepage ratio parameter is occurred for defected zone location that established out of dam body. The gradient in foundation beneath the defected zone for case of foundation permeability of $K=10^{-2}$ m/s is almost close and falls in narrow range between 0.28 and 0.38. The higher gradient within the weakness zone in No. 4 location is consequent of relative difference in permeability between the foundation and defected zone. When the

foundation is more permeable than the weakness zone of impervious blanket, more water energy head drop should be happened in defected zone to satisfy the continuity flow law of water discharge from defected zone into foundation. Thus, the higher drop of water head along a short path (equal to blanket thickness) causes to generate a higher magnitude gradient in defected zone in case of permeable foundation. The extra gradient of 5.6 for the defected zone location of No. 4 may lead to more erosion in defected zone which cause to develop the weakness zone and the weakness area is further enhanced. Also, as though earlier, enlarging the defected zone width in case of permeable foundation directly causes to increase the discharge and will be act as accelerate factor of defect.
In contrast to the higher permeable foundation, if foundation has the lowest permeability (i.e. $K=10^{-6}$ m/s), insignificant gradient force is generated within the defected zone and, in turn, the extra gradient is developed in foundation beneath the defected zone. In this case, the critical condition occurs in defected zone location of No. 1 where the impervious blanket is connected to the clay core. For this location, the gradient of 2.8 is recorded in foundation. Furthermore, for defected zone located in mid width of dam body (i.e. location of No. 2), the gradient of 1.14 is recorded. For other locations, the gradient is relatively high, but less than unity. Generally, by increasing the distance of defected zone from dam core, the gradient in foundation is decreased. Existing extra gradient further than unity in foundation comprised of fine grained and low permeability soils implies that besides the weakness zone of impervious blanket, the foundation beneath the weakness zone is susceptible to erosion due to high gradient force and defect can be transmitted to foundation layer. The erosion in foundation may lead to extra local settlement beneath the impervious blanket and intensify the weakness zone in blanket.

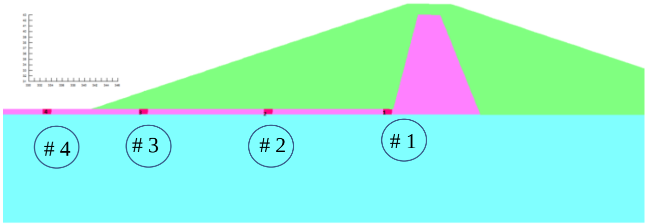

Figure 6. The location of defected zone that hydraulic gradient is measured

Table 2- The maximum hydraulic gradient within defected zone

Location No.	Distance from clay core (X) m	$K_{foundation}=10^{-2}$ m/s	$K_{foundation}=10^{-4}$ m/s	$K_{foundation}=10^{-6}$ m/s
1	0	0.4500	0.1500	0.0030
2	40	0.5000	0.1000	0.0015
3	60	0.5600	0.0900	0.0010
4	80	5.600	0.1000	0.0007

Table 3- The maximum hydraulic gradient in foundation beneath the defected zone

Location No.	Distance from clay core (X) m	$K_{foundation}=10^{-2}$ m/s	$K_{foundation}=10^{-4}$ m/s	$K_{foundation}=10^{-6}$ m/s
1	0	0.36	1.16	2.80
2	40	0.34	0.74	1.14
3	60	0.38	0.55	0.59
4	80	0.28	0.54	0.39

6. CONCLUSIONS

In this paper, the seepage through defected zone occurred in upstream water tightening blanket system is investigated. The following consequents from numerical analyses can be summarized:

- The location defected zone in upstream impervious blanket directly influences the seepage pattern through dam body and foundation. If the defected zone is occurred in the situations close to the dam core, escaping water from weakness zone of impervious blanket impact the clay core water tightening performance and water potential head drop is not completely occurred in clay core.
- If the permeability of foundation is high, the magnitude of water seepage discharge in foundation that entered through defected zone tended to increase by growing the defect zone area. In contrast, in dam

underlying on the foundation with lower permeability, the width of defected zone area has no effect on the enhancing the discharge through foundation.

- From the erosion potential view, the critical condition is the case that the defected zone in upstream blanket is occurred out of dam body and the foundation has the higher permeability. In this condition, the gradient of 5.6 is recorded in defected zone. For this type of dam, the gradient in foundation is insignificant.
- If the foundation has lower permeability and defected zone is occurred in impervious blanket next to clay core connection point, the foundation beneath the defected zone is susceptible to erosion due to significant extra gradient in this point that exceeds unity. By moving defected zone location far away the dam core, the hydraulic gradient in foundation tend to decrease and fall less than one.

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