EFFECT OF FLUID FLOW CHARACTERISTICS OF ANTI-SEEPAGE MATERIALS IN DAM STRUCTURES

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ABSTRACT

The use of concrete for hydraulic structures has special requirements for water and its penetration through the concrete, and the effect of different aggressive agents on the concrete and its components. The requirements are much higher on permeability and durability than in the case of mechanical properties. While in the case of mechanical effects, stress concentrations are greater in region of higher quality concretes (rigidity and strength), the water flow line follow the weaker planes of increased permeability.

This paper reviews typical values of design seepage coefficient from literature and also uses the experimental results of a laboratory study done for clay-cement concrete material. The clay-cement concrete studied was designed to be a low-strength material and its properties fall between those of soil and concrete. The material may be used as anti-seepage material in the foundation and diaphragm wall in earth dams, and canal lining in channel constructions. The three main design criteria considered for anti-seepage requirements, i.e. permeability, deformity, and long-term performance are used in the dam analysis with emphasis on water permeability. Water flow effect in hypothetical earth dam cases were assessed using a finite element-based software program to determine the influence of the design water permeability of cut-off wall based on the seepage regime that develops as a result of the barrier construction.

It was found that construction of an anti-seepage barrier is effective in reducing the hydraulic gradient, even if the permeability coefficient of the barrier is several orders of magnitude high. Results also indicate that clay-cement concrete anti-seepage effect potentially gives high performance. This study may contribute a better understanding of the fluid flow characteristics in dams having a cut-off wall for improved practices and anti-seepage materials.

INTRODUCTION

Use of anti-seepage materials in dam foundation and water tightening using diaphragm wall construction are measures applied to control seepage, reduce uplift pressure under the dam, and appurtenant structures, and to prevent sliding of downstream structures resting on weak ground layers. Grout curtain and cut-off wall are two conventional methods for water tightening of large dams seepage controls. The most common method used to seal the rock foundation is grouting. Where the foundation of a dam consists of pervious alluvial layers, grouting methods such as sleeve pipe, jet grouting and chemical grouting have been successfully employed. As an alternative, cut-off walls can be used.

Cut-off wall performs as an underground seepage barrier to control underground water flow. The selection of material used in the wall is based on require wall performance, construction facilities and the surrounding ground specifications. A wide range of cut-off wall materials have been used including compacted impervious soil, reinforced soil, soil-bentonite, plastic concrete, conventional concrete and reinforced concrete. Usage of materials such as geosynthetics, asphalt concrete, clay-concrete or clay-cement concrete and mixed soil has also been reported, while sheet pile wood, plastic or metal material have been seldom used[1]. There are several types of embankment dams. The designs have varying degrees of in-built conservation, usually relating to the degree to which seepage within the dam is controlled by provision of filters and drains, and the control of foundation seepage by grouting, drainage and cut-off construction[2].

In this paper, five common field cases for the fluid flow characteristics of anti-seepage materials are analyzed based on design permeability coefficient obtained from the literature. In all cases, the seepage analysis was done using finite element seepage module of the computer program Phase2 Version 7.0 of RocScience[3]. The analysis only considered the fluid flow behaviour of anti-seepage materials, i.e. deformation of the dam is ignored and all displacement degrees of freedom are prescribed to zero. The total head of 40 m was fixed in order to simulate full reservoir steady state seepage.

CASE STUDIES OF DAMS

Case 1. Nandoni Dam, located in Thohoyandou town of Limpopo province, Republic of South Africa. The dam has a maximum height of 47 m, and was constructed during the period of October 1998 to August 2005[4].
The earth embankment dam rests on virtually decomposed variants of diabase and granite rock foundation with ponded water elevation of 40 m on the left side.

Case 2. An earthen dam with unconfined flow[5].
This is an analysis of unconfined flow through a multi-layered earth dam founded on rock. The model includes drains, sand blankets, and a grout curtain below the core. Six different materials and their permeabilities ranging from $5x10^{-3}$ to $5x10^{-7}$ m/s[5] were used in analysis. It is assumed that all the materials are isotropic.

Case 3. Hypothetical dam: Composite stabilized soil dam consisting of 10% soil-cement facing and 7.5% soil-cement "hearting" [6].
Robertson[6] used the Rondebosche dam as a case study to compare the costs of alternative structures. Data were available for the concrete buttress dam constructed at the site, as well as for an alternative (proposed) earth embankment dam. By varying the stabilizer content, the specific 'zones' required in the embankment can be provided. For example, a cement rich upstream facing of 10% soil-cement can be used simultaneously as an impermeable membrane and as slope protection. The protection layer of approximately 600 mm thickness is constructed by compacting horizontal layers of soil-cement typically 2 to 3 m wide, and 150 to 300 mm deep in stair step fashion up the embankment. It should be noted that the same technique is used in roller compacted concrete construction[12].

In this case, the permeability of the stabilized soil is an important consideration in the design of homogeneous stabilized soil embankment dams. The measured permeabilities of the stabilized materials ranged from $2x10^{-11}$ m/s to $2x10^{-8}$ m/s[7]. Since these permeabilities fall within the range of permeabilities acceptable for an impervious core, it would not be necessary to include other impermeable elements to reduce seepage losses if these stabilized soils were used in a dam. Three materials and their seepage coefficients are considered, i.e. 10% soil-cement facing, 7.5 % soil-cement hearting and incompressible foundation taken to be impermeable since the model is only concerned with the fluid flow of anti-seepage materials.

Case 4. Hypothetical dam: Composite stabilized soil dam consisting of 10% soil-cement facing and 7.5 % soil-lime "hearting"[8] *for the homogeneous embankment, and same foundation condition as in Case 3.*
The strength and durability properties of lime-stabilized soils are generally lower than the corresponding properties of cement stabilized soils [7]. A direct comparison is however pointless since the choice of stabilizing agent for a particular application is dependent on the soil type and in particular the quantity and type of clay present in that soil. Bentel[7] found that for a soil containing heavy clay, adding a given quantity of lime may sometimes result in material properties superior to those obtained by adding a similar quantity of cement.

Case 5. Composite stabilized soil dam (10% soil-cement facing and 7.5 % soil-lime "hearting") of thick clay-cement concrete foundation slab and cut-off wall connection in T-shape fashion.
The soil stabilized embankment of the dam i.e.10 % soil-cement and 7.5 % lime-cement, is founded on clay-cement concrete, which has a lower stiffness than conventional concrete, making it possible to adapt to deformations on compressible foundation[12]. The mix of clay, cement and aggregates is designed to correspond to the requirements of similar water-impermeability as the embankment. The mix should be workable and typically of composition: water / (cement + clay) = 0.85 and clay/ cement =2/ 3 or 40% clay content. Its compressive strength is usually greater than 6 MPa while its permeability ranges from $5x10^{-10}$ to $1x10^{-11}$ m/s. Figure 5a indicates how the cut-off wall is used in the dam for the control of seepage. In literature, large dams with slightly sloping core, were also built in Macedonia, Turiya dam[9]. The embankment is 80 m high and made of a thick layer of alluvial sediment while the clay core is founded on mass of clay-concrete. The mixture of clay-concrete consists of: dry mass/ water = 2/1 and clay/ cement = 3/1 and has compressive strength greater than 1.5 MPa.

In general, Cases 1 and 2 are the unstablised soil embankments while the others, Case 3 to 5 are stabilized dam embankments. Table 1 gives the permeability coefficients applied in analysis of the cases.

SEEPAGE ANALYSIS BY FINITE ELEMENT METHOD

Seepage analysis of dams has been done by using a finite element-based software program to determine the influence of design water permeability of the cut-off wall based on the seepage regime that develops as a result of the barrier construction. The effect of using clay-cement concrete is analyzed and compared with other anti-seepage materials. In the analysis dam, foundation and different anti-seepage materials of hypothetical earth dams are modeled using the computer software[6]. The cut-off wall extends below the clay-cement concrete slab and is fixed into an impervious layer. Material permeability is required by the finite element analysis in order to solve the seepage problem. Permeability, K_2/K_1 is a factor which specifies the relative permeability in the direction orthogonal to the K_1 direction. Note that the K_1 permeability is the "primary" permeability defined by the saturated permeability K_s. K_1 Angle is the angle which specifies the direction of the K_1 permeability and is specified relative to the positive x (horizontal) direction. In the analysis, it is considered that, K_2/K_1 =1(unity) and K_1 angle = 0, i.e. the permeability in the horizontal direction = K_s (in saturated zone), and the permeability in the vertical direction = 1x K_s (in saturated zone). The set boundary conditions are total head (H), Zero pressure (p=0) and the Unknown (?), a special boundary condition that automatically determines whether the surface is a seepage face (zero pressure, p=0) or no flow boundary (Q=0). Examples of details of the finite element analysis set up are shown in the Figures 1a and 2a for Cases 1 and 2 respectively.

Table 1 Hydraulic (permeability) properties of Case 1 to 5

Case 1 parameter	Upstream rip rap	Upstream graded gravel	Semi-pervious zone	Clay core	Filter	Grout curtain	Rock foundation
Coefficient of permeability [2,10-11] (m/s)	$1x10^{-1}$	$1x10^{-3}$	$1x10^{-7}$	$1x10^{-9}$	$1x10^{-6}$	$1x10^{-6}$	$5x10^{-10}$
Case 2 parameter	Shell	Random	Clay Core	Filter	Grouted zone		Rock foundation
Coefficient of permeability [5] (m/s)	$5x10^{-3}$	$5x10^{-5}$	$5x10^{-7}$	$5x10^{-4}$	$5x10^{-5}$		$5x10^{-4}$
Case 3 parameter	10 % soil-cement facing		7.5 % soil-cement “hearting”		Incompressible foundation		
Coefficient of permeability [6] (m/s)	$1x10^{-11}$		$1x10^{-8}$		$1x10^{-20}$		
Case 4 parameter	10 % soil-cement facing		7.5 % soil-lime “hearting”		Incompressible foundation		
Coefficient of permeability[6,7] (m/s)	$1x10^{-11}$		$1x10^{-8}$		$1x10^{-20}$		
Case 5 parameter	10 % soil-cement facing		7.5 % soil-lime “hearting”		Cut-off wall and slab		Compressible foundation
Coefficient of permeability[2,6,7](m/s)	$1x10^{-11}$		$1x10^{-8}$		$1x10^{-11}$		$5x10^{-4}$

PRESENTATION AND DISCUSSION OF RESULTS

A summary of the results is presented along with Figures 1b to 5d giving the output results for each of the case studies.

In Case 1, the hydraulic gradient ranges from 1.5 to a maximum of 10 shown in the display of flow lines in Figure 1b. The higher gradients calculated in Case 1 ranges from 3 to 10 occurring at the crest above chimney drain, and could be considered erosive to soils if not protected by effective filtering. The water table surface of 40 m total head drops down to chimney drain that is connected to the blanket drain from which all the water will drain down by the toe drain at downstream end. The boundary gradients of clay core grout curtain were calculated as 1.93 and 1.97 respectively while the gradients in the clay core grout curtain on the left side and right side were 2.08 and 2.68. It is clear that the maximum gradient occurs at the vicinity of the connecting section of the clay core and grout curtain. The gradients above the blanket drain towards the semi-pervious zone at the downstream side were found to be 0.78 to 0.80. And, the exit gradient at the toe drain is 0.46.

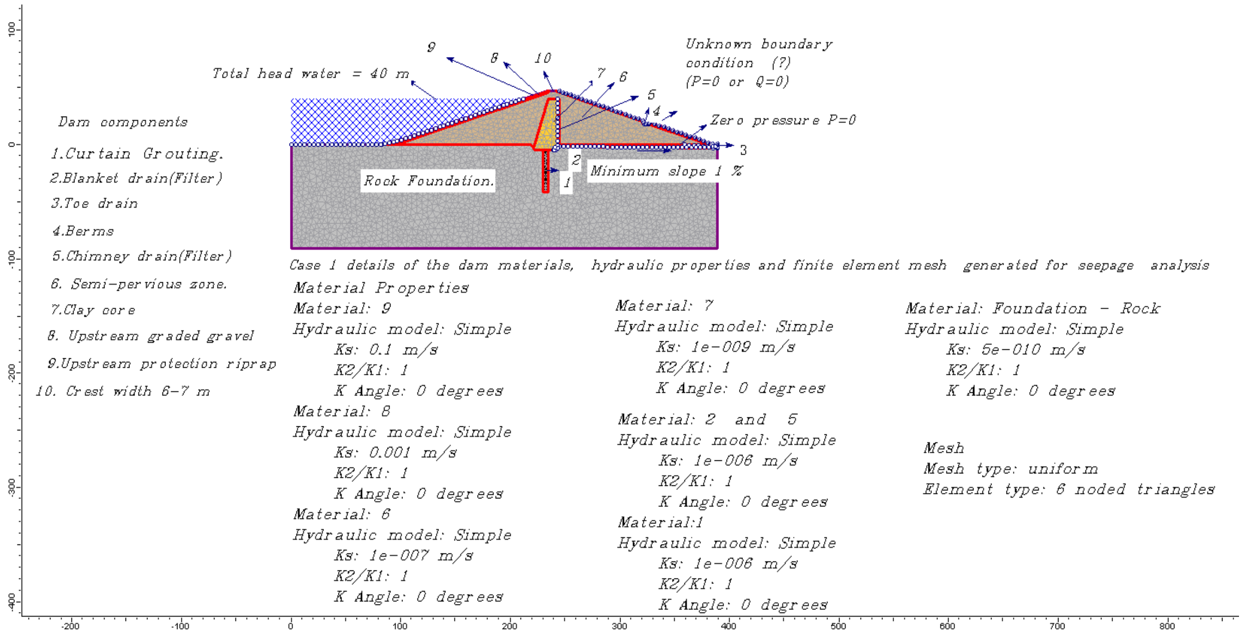


Figure 1a Details of Case 1

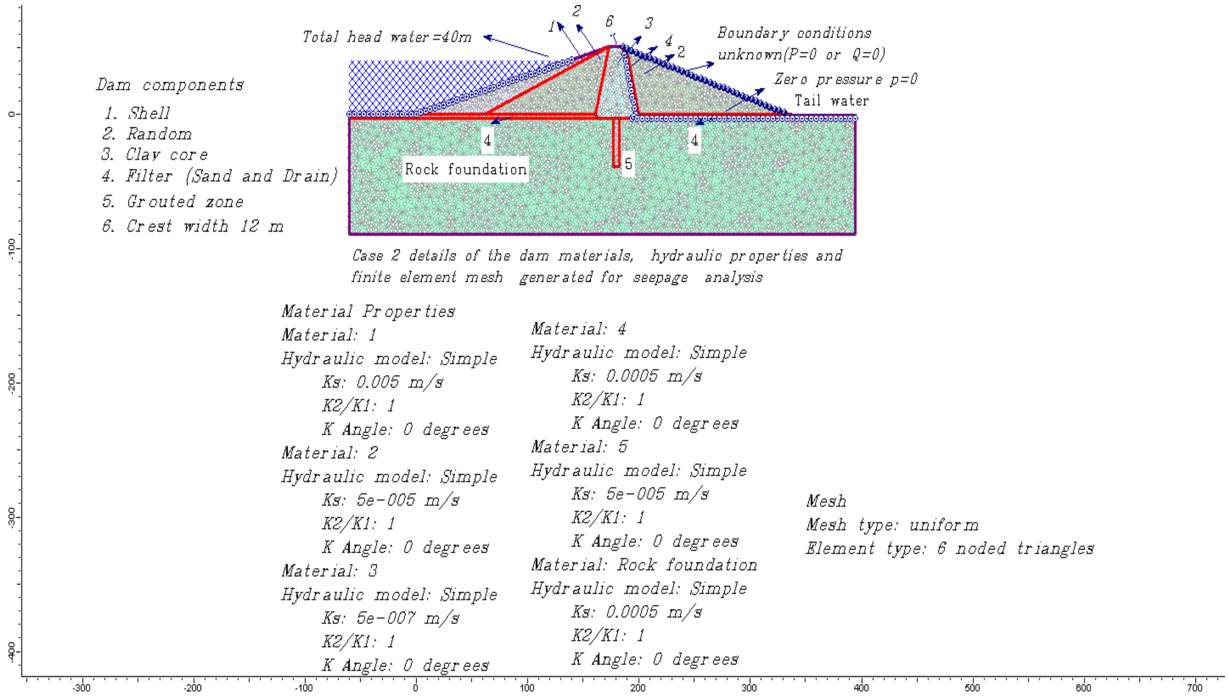


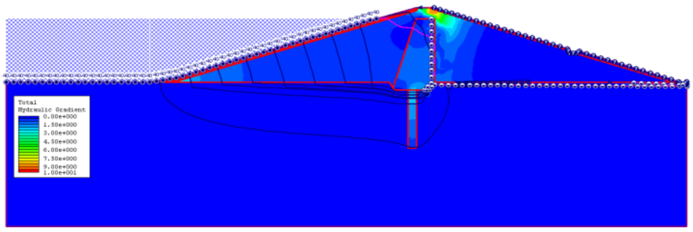
Figure 2a Details of Case 2

In Case 2, in between clay core and random boundary the gradient varies from 0.45 to 0.90, while the gradient inside the core is about 0.9 to 1.8. At the exit in downstream side, the gradient is constant and drops down by filter interceptor. The grout zone for foundation treatment has gradients of 1.8 to 2.25, shown in Figure 2b. In this case, there is evidence (from flow lines) that the increased gradient may be acting to erode rock-grout zone joint infill in the foundation treatment. However, if this process occurs, it will be localized and has a small effect on the overall dam performance. The core restricts water flow almost completely. Most flow will occur through the sand drains and the rock. The grout curtain is not very effective in altering flow as its permeability is not much different from the surrounding rock as given Table 1. The results of Case 2 are in agreement with literature indicating an unconfined flow through a multi-layered earth founded on rock[5]. At the boundary of clay core and grout zone, the maximum gradients are 1.15 and 2.17 respectively while the gradients in clay core-grout zone on the left and right side are 2.17 and 2.09. Since the type of flow is unconfined, the hydraulic gradients are distributed along filters i.e. sand, blanket and chimney drains. The exit gradient reduces to zero at the tail water pond located downstream at end of the dam.

The stabilized soil embankments, given in Figures 3 and 4a for Cases 3 and Case 4 respectively are considered similar due to the same design seepage coefficient values used as material property. Since in both cases, the dams are founded on incompressible foundation which has very low seepage coefficient of 1×10^{-20} m/s, it can be assumed that the foundation is essentially impermeable. For Case 3, the low gradients of 0.25, 0.51, 0.76 and 1.02 are experienced in the upstream side, in areas underlying the embankment. At these locations, the analyses indicate no significant change in the erosion mechanism of concern and, consequently, exit gradients 1.28, 1.53 and 1.70 do not appear to be eroding downstream slope protection[9]. Since both dam cases have similar embankment and foundation conditions, the results for hydraulic gradient in Case 4 are of the same trend as Case 3 with small differences in value. Figures 4b to 4e give the boundary gradients from “hearting” to facing then downstream end and exit gradient for dam Case 4.

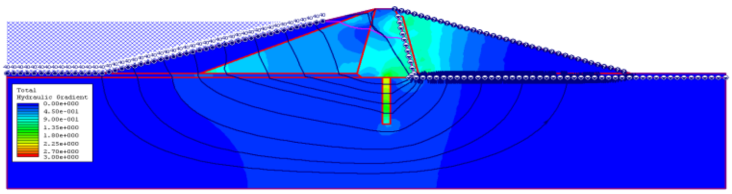
Case 5 dam has similar embankment condition with Case 4 but it is founded on compressible foundation with the permeability coefficient of 5×10^{-4} m/s. The calculated hydraulic gradient of 2.5 arises at left side of upstream leveling slab while zero gradients are experienced below the clay-cement concrete seepage barrier in the foundation. But this reduction in the gradient has consequences leading to higher gradients of 4.5, 6.7,9 and above on the end of downstream side as shown in Figure 5a. This will result in much higher erosion potential for connection between outer shell soil-cement and leveling foundation slab of clay-cement concrete. The behaviour of water flowing through cut-off wall was calculated below boundary of clay-cement concrete material and found to be less than 0.003 as given in Figure 5b. Similarly, the hydraulic gradients developed in the peripheral of soil-lime and soil-cement embankment are shown in Figure 5c. The average hydraulic gradient in the peripheral soil-cement & soil-lime is less than 1 and drops to zero up to some distance then increasing alarmingly in the downstream side up to about 7.9 before dropping again to 6.0 as shown in the Figure 5c. Below the barrier from left to right the gradient drops from 0.003 to zero then up to about 0.0025 then decreases to zero. Over all along the slab the hydraulic gradient falls in between 0.0005 and 0.001. The seepage barrier construction in Case 5 causes higher increments in hydraulic gradients at downstream ends of the embankment, giving 7.9 compared to the maximum of 1.47 in Case 4 founded on incompressible foundation, and 1.17 for Case 4-Special designed with no barrier, and a compressible foundation of 5×10^{-4} m/s permeability coefficient.

Comparison of boundary gradients indicates that use of clay-cement concrete in Case 5 reduced the gradient to 0.04 (fig. 5d) as compared to 0.70 and 0.28 for Case 4 with incompressible / compressible foundation respectively. Exit gradient was reduced by 99.5 % for Case 5 (See fig. 5d), 42.1 % for Case 4 (See fig. 4d) and 49 % for Case 4-Special (See fig. 4e). The maximum gradients calculated for the “hearting’ section (middle) are 1.30 of Case 4, 0.33 for Case 4-Special, and 0.37 for Case 5. By considering change of gradients from the maximum values at the 'hearting' to gradients at exit level, it can be seen that the best performance was found in Case 5 (made with clay-concrete foundation) giving a gradient reduction of 89.2%, followed by Case 4 with 46.2%, and Case 4-Special with 15% gradient reduction. Due to presence of the clay-cement concrete barrier, the seepage forces are concentrated at the barrier location rather than distributed across the embankment as in situations with no barrier in place. This is evident from observations in Figures 5c, 4b and 4c. These concentrated seepage forces, however, can result in deformation of the barrier which in turn may cause cracking in rigid barriers.



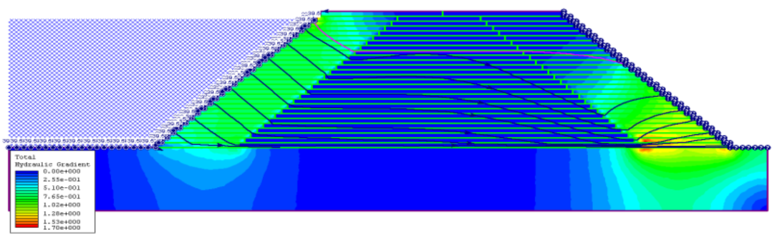
i_t
0
1.5
3.0
4.5
6.0
7.5
9.0
10.0

Figure 1b: Display of total hydraulic gradient (i_t) and flow lines Case 1



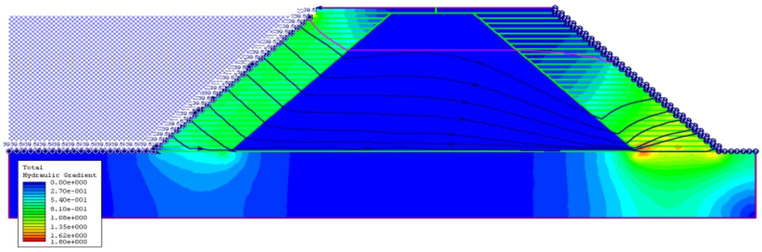
i_t
0
0.45
0.90
1.35
1.80
2.25
2.70
3.00

Figure 2b: Display of total hydraulic gradient (i_t) and flow lines Case 2



i_t
0
0.25
0.51
0.76
1.02
1.28
1.53
1.70

Figure 3: Display of total hydraulic gradient (i_t) and flow lines Case 3



i_t
0
0.27
0.54
0.81
1.08
1.35
1.62
1.80

Figure 4a: Display of total hydraulic gradient (i_t) and flow lines Case

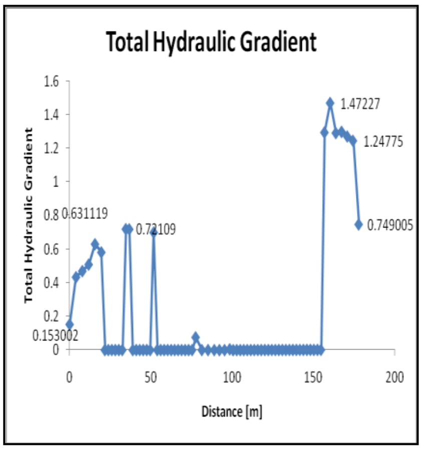


Figure 4b: Case 4 facing and 'hearting' embankment

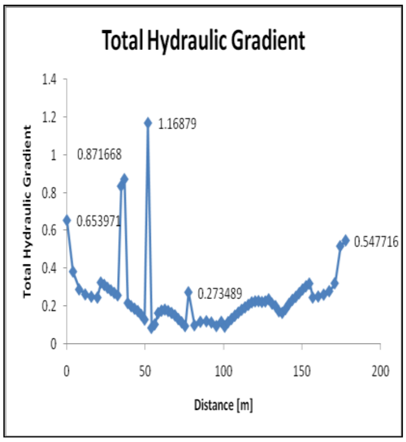


Figure 4c: Case 4 on compressible foundation facing –'hearting'

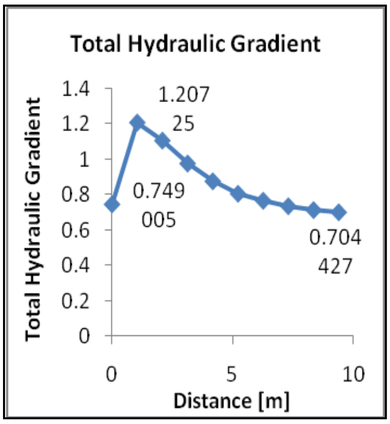


Figure 4d: Case 4 facing to downstream end continued from Figure 4b

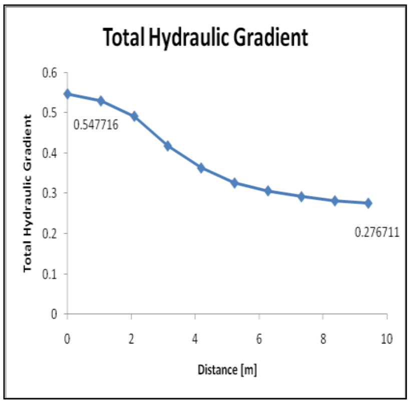
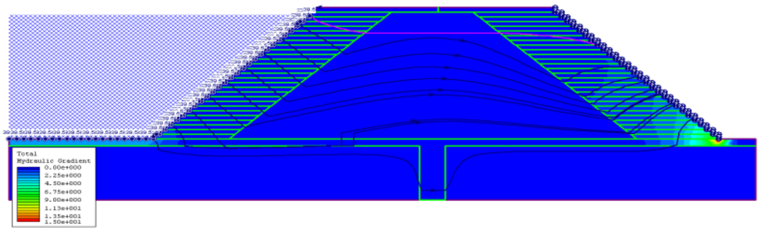


Figure 4e: Case 4-Special with compressible foundation (no barrier in place) continued from Figure 4c



i_t
0
2.25
4.50
6.75
9.00
11.3
13.5
15.0

Figure 5a: Display of total hydraulic gradient (i_t) and flow lines Case 5

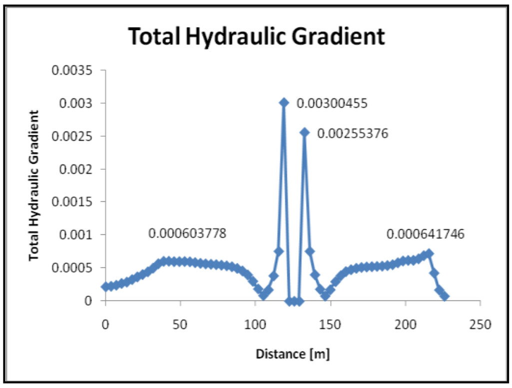


Figure 5b: Below the slab and cut-off around

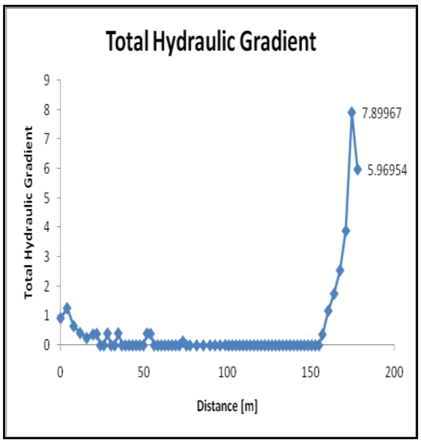


Figure 5c: Case 5 facing and 'hearting' embankment

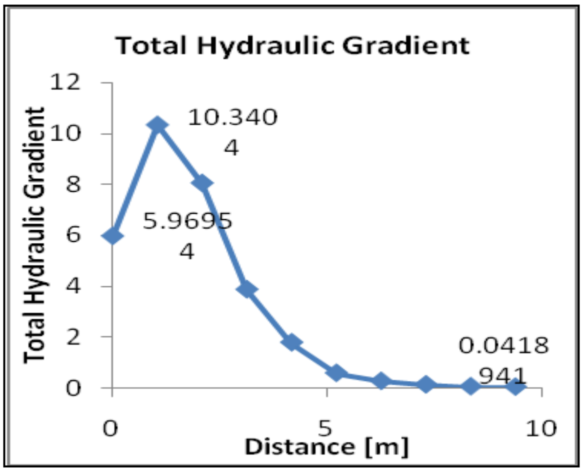


Figure 5d: Case 5 facing to downstream end continue from Figure 5c

CONCLUSIONS

The foregone analysis illustrates that the magnitude of hydraulic gradient that develops at the peripheral of an anti-seepage material is a function of multiple factors. It is important that each dam and its anti-seepage materials are analyzed individually to assess the potential for development of high hydraulic gradients.

In the anti-seepage analysis conducted, it was found that construction of clay-cement concrete barrier leads to reduction of the exit gradients by a range of about 89% at the middle section or “hearting” to 99% at the downstream exit. Also, where high gradients existed at a location facing downstream, the seepage barrier is effective in reducing the gradient, even if the permeability coefficient of the barrier is higher than that of the foundation. This reduction in exit gradients has the effect of reducing the flow volume through the dam by several orders of magnitude.

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