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Research Note

Effect of Geometry and Foundation Conditions on the Accuracy of the Steady State Seepage Analysis Results for Rockfill Dams

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One of the most important concerns in designing an embankment dam is seepage analysis. Conventional seepage analyses of embankment dams are performed in two-dimensional (2D) space, in which the impacts of water flow lines seeping from the side abutments are ignored. This fact is especially important if the dam is constructed in a narrow valley. In addition, if the effects of existing underlain faults in the reservoir water discharge rate, under different loading conditions, are to be scrutinized, three-dimensional (3D) modeling of the dam for seepage analysis is inevitable. In this paper, the significance of three-dimensional seepage analyses is emphasized by making a 3D model of a real dam site. The assumed 3D model contains all details of the rock-fill dam body and its foundation and abutments. Also, all ground improving methods for the water tightening of the underlain faults have been considered. The 3D steady state seepage analysis results were compared to those of a 2D analysis, from different points of view, indicating that when a dam is designed for a narrow valley, performing a 3D seepage analysis is vital, due to the widthwise water flow from the side abutments. Several sensitivity analyses were also performed to show the effect of uncertainty in evaluating the characteristics of side abutment grouting curtains in seepage analysis results.

INTRODUCTION

In numerical simulations, it is usually intended to simplify the real structure by eliminating regions that are believed to have minor impact on a desired result. This is mainly due to the lack of proper simulating tools, as well as insufficient knowledge of the true mechanism of a phenomenon and the relevant affecting factors. One of the important stages in the design of earth and rockfill dams is the exact evaluation of water discharge rate, hydraulic gradients and pore water pressure in various parts of the dam, to ensure stability and avoid endangering effects, such as piping and slope instability. Most engineers make a two-dimensional model of an embankment dam. This consideration requires such simplifications as eliminating the effect of widthwise water flow through side abutments and the effect of side watertight elements. In this way, two-dimensional seepage analysis is believed to render inaccurate results, especially when the abutment materials are of high permeability, which results in a higher downstream water level and discharge rate.

In this paper, two and three-dimensional seepage analysis of an embankment dam are performed to investigate the following cases:

1. To compare the results between two and three-dimensional analyses;
2. To justify the appropriateness of three-dimensional seepage analyses in special situations, such as V-shaped valleys and the existence of faults beneath the dam structure;
3. To illustrate the degree of dependency of seepage analysis results on some affecting factors, such as material permeability and size of watertight elements.

THEORY

The governing partial differential equation used in the formulation of the unsteady (transient) seepage

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analysis in 3D space is, as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)+Q$$
$$=\frac{1}{1+e}\left(e\frac{\partial S}{\partial t}+S\frac{\partial e}{\partial t}\right), \qquad (1)$$

where k_x, k_y and k_z are the coefficient of permeability functions in the x, y and z directions, respectively; h is total head, Q is flux at the model boundaries, S is saturation percentage, e is void ratio and t is time. Four flow conditions exist, based on the variation of e and S in the above equation:

1. Steady state flow for constant values of e and S,
2. Consolidation for decreasing e or expansion for increasing e, assuming constant value for S,
3. Constant-volume drainage for S decrease and saturation for S increase at constant e,
4. Compression and expansion situations for varying both e and S [1].

For steady state flow conditions, the right hand side of the above equation vanishes, due to the constant values of e and S.

In this paper the three-dimensional finite element analysis is used to simulate the dam site. The finite element technique is a particularly valuable numerical method, as it readily accumulates complex boundary geometry, anisotropic permeabilities and simple or complex layering [2-4]. This method requires the discretization of the soil mass into elements.

The finite element formulation for steady state seepage in three dimensions has been derived using the Galerkin principle of weighted residuals [5]:

$$\int_v [B]^T[C][B])\, d_v\{H\} = \int_A A\;\; q\langle N\rangle^T\langle N\rangle)\, dA, \qquad (2)$$

where:

$[B]$ = gradient matrix,
$[C]$ = element hydraulic permeability matrix,
$\{H\}$ = vector of nodal heads,
A = area of the face of the element,
q = unit flux across the face of an element,
$\langle N\rangle$ = vector of interpolating functions.

For steady state seepage analyses, the coefficient of permeability is constant, with respect to time at each point in saturated soil, however, in unsaturated soil, the water coefficient of permeability is a function of water content and $(u_a \quad u_w)$ stress state variable and, with u_a remaining constant, the change in volumetric water content is a function only of pore-water pressure changes and varies from one point to another within the soil. u_a and u_w are void pressure and pore water pressure; respectively. The flow of water through both saturated and unsaturated soil follows Darcy's law, which states that:

$$v = ki, \qquad (3)$$

where, k is water coefficient of permeability and i is hydraulic gradient.

Research has shown that, in steady state seepage problems, a typical permeability function will give the results close to those of exact permeability functions [6,7]. The typical permeability function for core material is depicted in Figure 1.

CASE STUDY

In this study, an under design stage, zoned rockfill dam, called Chakoo Dam, was considered for investigation. The site plan and a cross section at maximum height of the dam are shown in Figures 2 and 3, respectively. The 75 m high dam is located in the Province of Western Azarbayejan and in the Southwest of Piranshahr city. The Zab river, with a 20 m width, in the direction Northeast-Southwest, has an intense curvature in the dam site. The narrow V-shaped valley of the river is developed in conglomerate and left and right abutments have an inclination of 28 to 30 degrees to the vertical line. At the left abutment, the bored rock mass includes polymicte conglomerate protuberances, with the constituent particles of sandstone, limestone, silica and igneous stone, etc. Master joints or micro faults in the layers of 4 to 5 m are beneath a depth of 30 m. There is a fault, named F-1, with a 10 m crushed zone thickness and an inclination of 15 degrees to the vertical line at the left bank. There are two more faults, named F-2 and F-3, located at the river bed and right bank, with a crushed zone thickness of 2.7 and 7 m and an inclination of about 10 and 15 degrees from the vertical line, respectively. The river bed foundation consists of the moderately crushed zone

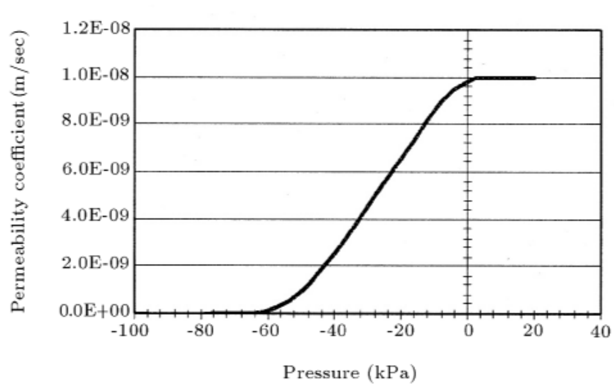

Figure 1. Typical shape of permeability coefficient of core material [5].

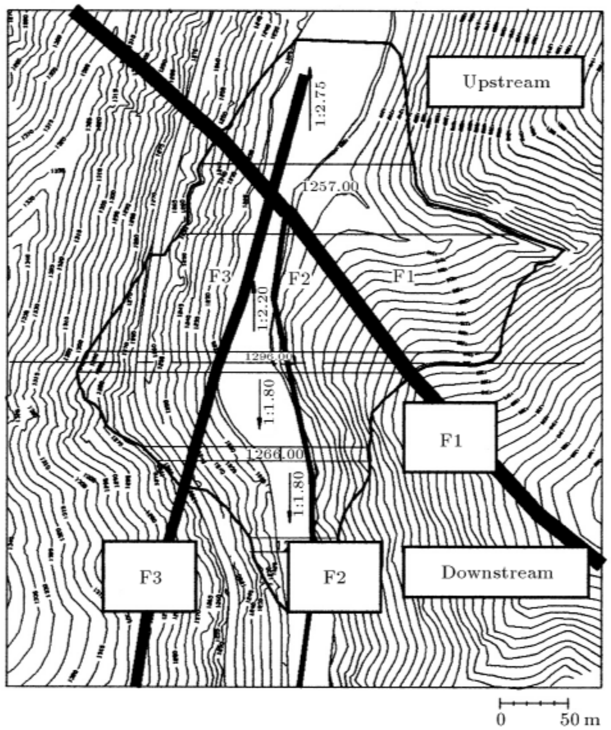

Figure 2. Site plane of the rock-fill dam and crossing faults (F1, F2 and F3).

to the depth of 10 m and the fresh one, afterwards, with discontinuities in the form of fractured to blocky and the RMR classification of fair to good rock. The right bank consists of the moderately to slightly weathered conglomerate to the depth of 11 m, with the fresh zone underlain. The coefficient of permeability is relatively high within a depth of about 55 m. As depicted in Figure 4, the considered seepage control method is a 60, 30 and 40 m height grouting curtain at the right, bed and left abutments, respectively.

The coefficients of permeability for various zones in dam body and foundation, according to the field geotechnical investigations and tests are depicted in Table 1.

MODELING

The dam site in this study was modeled in three-dimensional space using SEEP3D software, version 1, from Geo-Slope ™ Inc. Seep3D is a new finite element based software for modeling various three-dimensional

Table 1. Coefficient of permeability for various zones.

Zone	K_x (m/sec)	K_y (m/sec)
Core	1.0×10^{8}	1.0×10^{9}
Filter	1.0×10^{5}	1.0×10^{6}
Shell	1.0×10^{5}	1.0×10^{5}
Right Bank	1.3×10^{5}	1.3×10^{5}
Foundation	2.6×10^{7}	2.6×10^{7}
Left Bank	1.3×10^{7}	1.3×10^{7}
Crushed Zone	1.0×10^{5}	1.0×10^{5}
Grouting Curtain	1.0×10^{8}	1.0×10^{8}
Fault 1	1.0×10^{5}	1.0×10^{5}
Fault 2	3.9×10^{6}	3.9×10^{6}
Fault 3	3.9×10^{6}	3.9×10^{6}

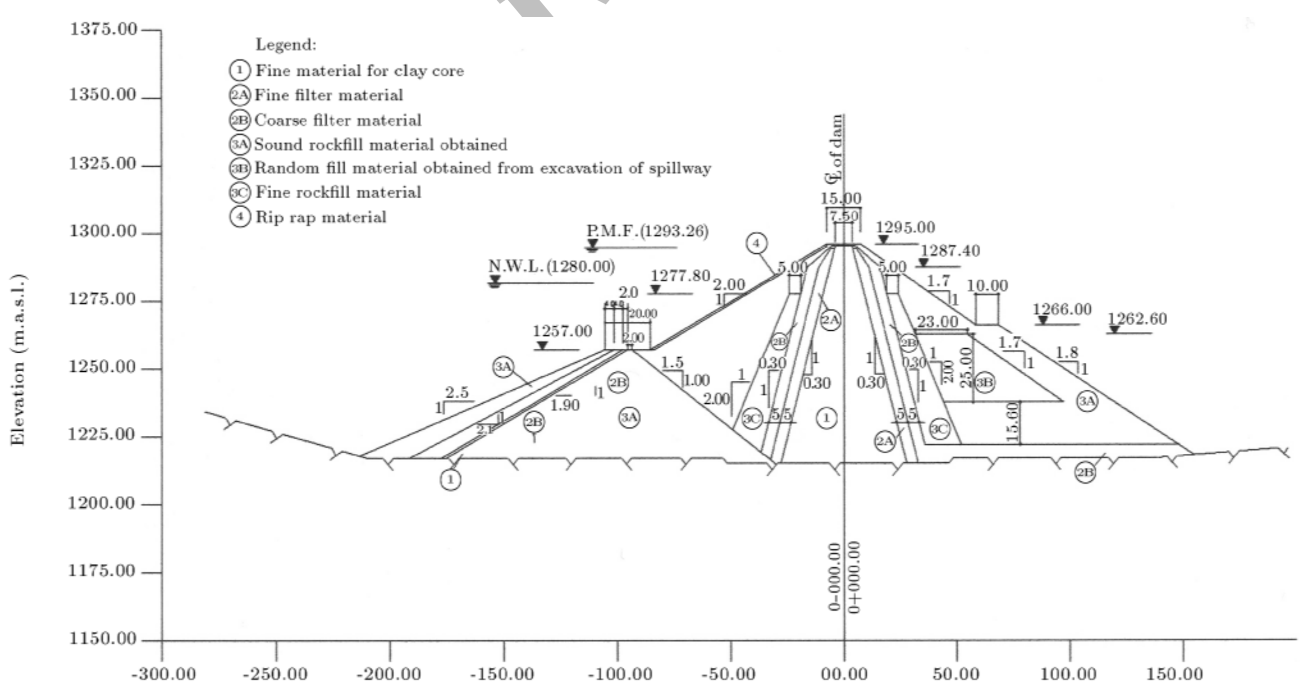

Figure 3. Cross section of the dam at maximum height.

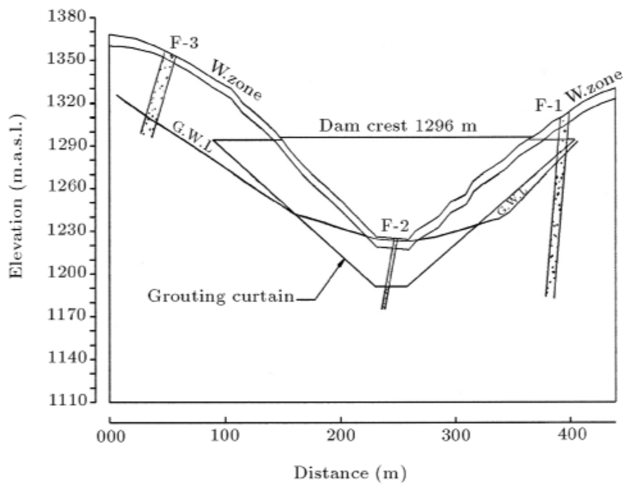

Figure 4. Longitudinal section of the dam (from upstream).

seepage problems [8]. Various zones were modeled, according to their geometry. Boundary conditions are comprised of a normal water level of 60 m in height, free surfaces having potential seepage at downstream surfaces, including the downstream shell, the downstream left and right abutments and the downstream foundation surface and, finally, a zero discharge rate from the remaining surfaces. The model site was at least extended from the dam axis to about 100 m from all horizontal directions. The foundation was modeled to the depth of 110 m below the riverbed. The finite element model of the dam site includes the model discretization into octahedral elements. Figures 5 and 6 show the 3D and 2D models of the dam site, along with their corresponding finite element meshing, respectively. The number of elements is selected, based on the accuracy of results. In this way, after applying the boundary conditions, the number of elements is increased to the stage where no further change occurs in the total downstream discharge rate. The results are summarized in Table 2 and show that 34493 elements are required to render an accurate result.

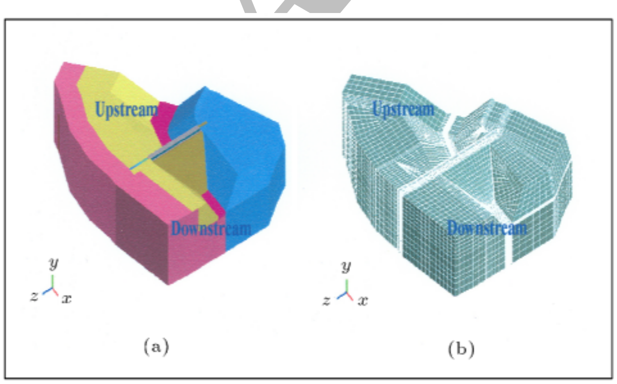

Figure 5. 3D model of the dam site (a), and its FE meshing (b).

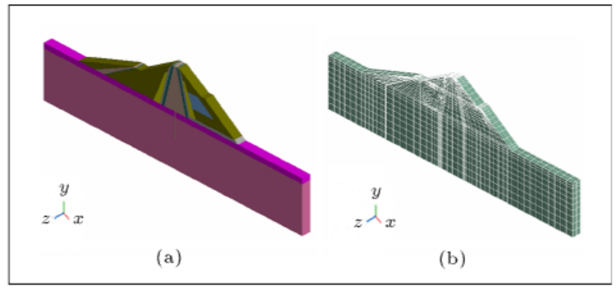

Figure 6. 2D model of the maximum section (a), and its FE meshing (b).

Table 2. Variation of discharge rate with the number of elements in 3D model.

No. of Elements	Discharge Rate (m^3/day)	Change
12852	1162.6	
23667	971.8	16%
34493	864.4	11%
48912	875.0	1%

RESULTS AND DISCUSSIONS

The steady state seepage analysis results, such as the water flux through the downstream part, phreatic surfaces and hydraulic gradients at the downstream toe, corresponding to several considered variations, were obtained and are discussed hereafter.

Comparison Between Two and Three-Dimensional Analyses

Figure 7 shows qualitative forms of the phreatic surface and flow lines obtained from the three and two-dimensional steady state seepage analyses.

More precise comparison between the two-dimensional steady state seepage analysis in the maximum section of the dam and those of the three-dimensional one is illustrated in Figures 8 and 9. Figure 8 shows that the water free surface in the downstream shell stands at a higher position in three-dimensional analysis compared to those resulting from the two-dimensional. This is mainly due to a widthwise water flow from the downstream side abutments to the shell. When the abutment materials are of high permeability, the effect of widthwise water flow on the downstream free surface will be more significant. Figure 9 compares the hydraulic gradient of the downstream toe for the results obtained from two and three-dimensional analyses. As indicated in the graph, the real hydraulic gradients are much higher than those obtained from the conventional analysis in two-dimensional space. For a 10 m grouting curtain depth, the 2D hydraulic gradient is 0.12, compared to that of

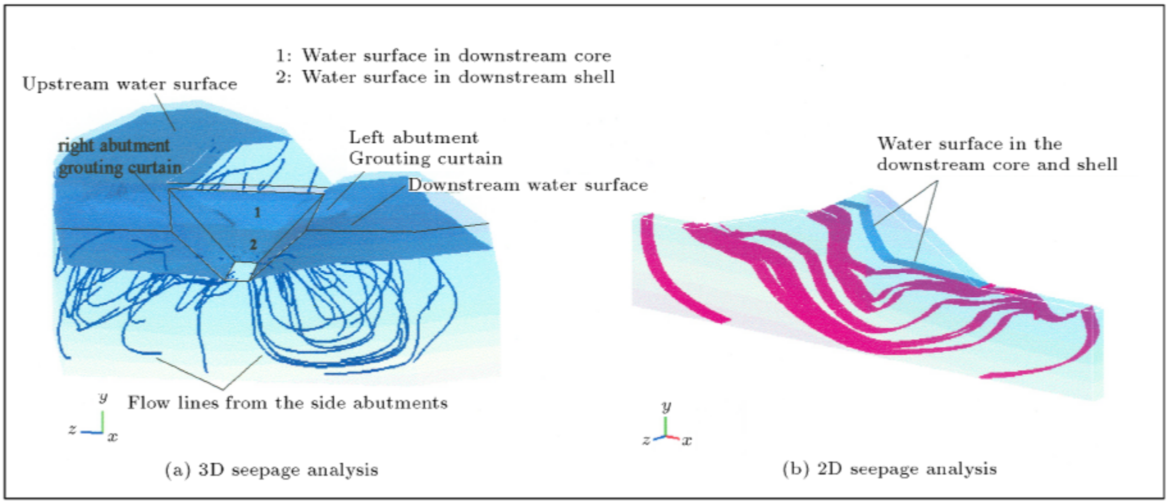

Figure 7. Water surface and flow lines in the dam site.

0.31 obtained from the 3D analysis. It is also indicated that, when the depth of the foundation grouting curtain passes the 10 m depth of the surface crushed zone and reaches the layer of relatively higher permeability, the 2D hydraulic gradient decreases rapidly, whereas, there is a steady reduction of the hydraulic gradient obtained from the 3D analysis when the grouting curtain has similar depth increases. This is because of the fact that, in 3D analysis, the main flow lines that create the hydraulic gradient at the downstream toe come from the downstream side abutments rather than the foundation and core of the dam, hence, increasing the height of the foundation grouting curtain has little impact on the reduction of the hydraulic gradient. This indicates that, in narrow valleys, seepage from the side abutments are of significant importance. This phenomenon is not usually considered when performing two-dimensional steady state seepage analyses.

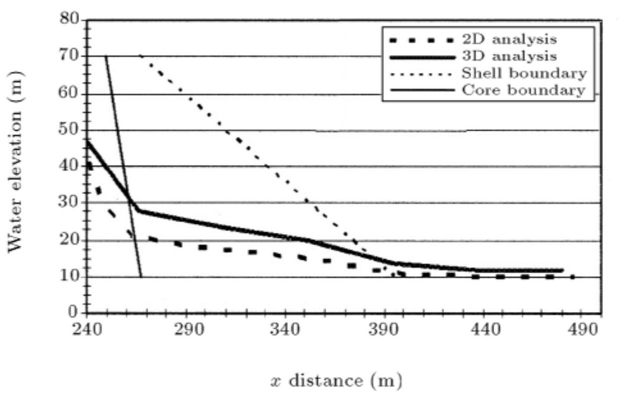

Figure 8. Comparison of downstream water level between 2D and 3D analyses.

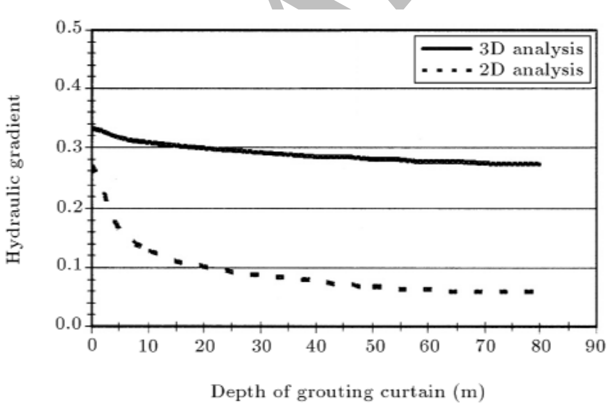

Figure 9. Comparison of downstream toe gradient between 2D and 3D analyses.

3D Fault Simulation

The existence of the three faults beneath the dam site in this case study, requires their simulation, especially when their effect in conducting water flow at the time of an earthquake might be activated. For the three faults that deviate from the vertical line in their cross section, indicated in Figure 4, and from the vertical line to the dam axis, indicated in Figure 2, two-dimentional simulation is impossible and, in order to obtain a comprehensive understanding of behavior of the faults in seepage analysis, three-dimensional simulation is required. The three faults, so called F1, F2 and F3 (Figure 2), were simulated in SEEP 3D, according to their corresponding geometry. Figures 10a and 10b show the model and its corresponding finite element mesh. In this case study, according to the available site geotechnical investigation results, the permeability of the crushed zone material within the fault planes is close to the permeability of the foundation materials. However, at the time of an earthquake, it is believed that the permeability of the fault materials will increase, with the high potential of conducting reservoir

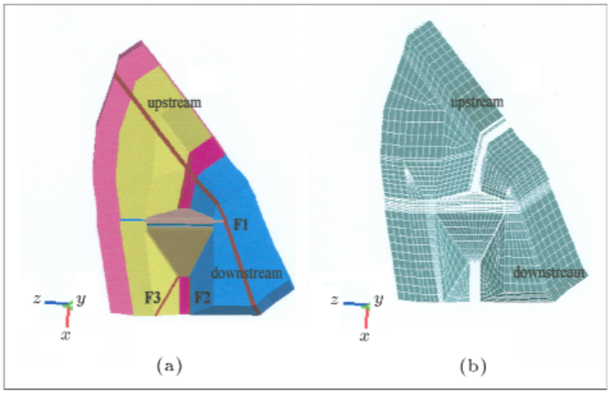

Figure 10. (a) Model simulation of the three faults; (b) The corresponding finite element mesh.

water from upstream to downstream. Therefore, simulations are performed by varying the hydraulic permeability of the crushed zone materials within the three fault planes and obtaining the corresponding discharge rate and hydraulic gradient. The results are depicted in Figure 11. This figure shows the variation of the discharge rate from the core and the total downstream discharge rate from 157 to 72530 m^3/day and from 1243 to 322970 m^3/day, respectively, corresponding to the variation of the permeability coefficient of the crushed zone material within the fault planes from the ratio of one to one thousand. With respect to the seepage problem of the rockfill dams, this increase in discharge rate is an endangering phenomenon that, in addition to the huge loss of reservoir water storage, increases the pore water pressure and piping, which severely affects the stability of the dam. One of the treatment methods for reducing the permeability of the crushed zone material is cement grouting up to a proper depth [9]. The effect of the depth of grouting curtain to the downstream discharge rate was simulated in SEEP 3D and the results are illustrated in Figures 12 and 13.

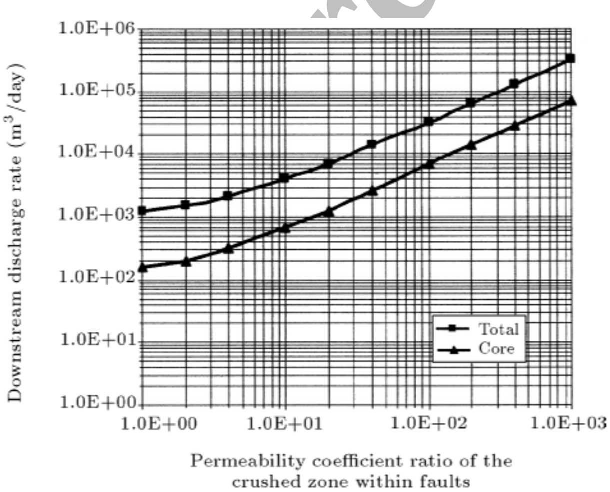

Figure 11. Variation of the downstream discharge rate with permeability of the fault materials.

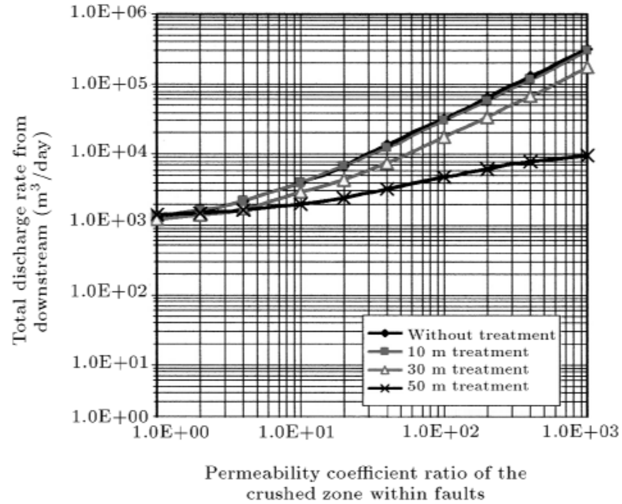

Figure 12. Effect of grouting treatment of the faults on the total downstream discharge rate.

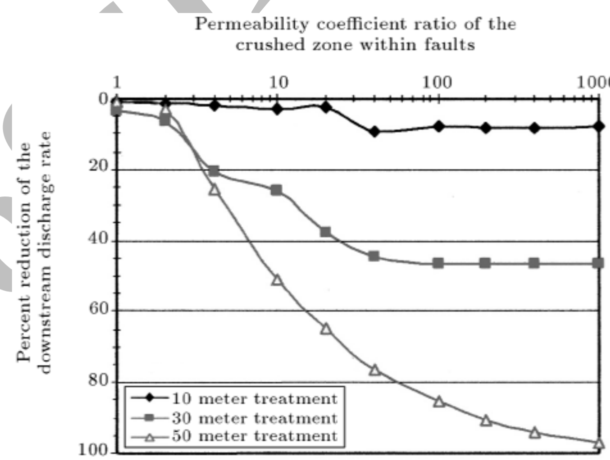

Figure 13. Reduction percent of the downstream discharge versus the fault permeability for different treatment depths.

Uncertainties Regarding the Side Abutment Treatments

In two-dimensional seepage analysis, the flux discharge rate from the side abutments remains unknown and the effect of side abutment material properties, depth and permeability of abutment watertight elements on the downstream water surface, hydraulic gradients and discharge rate, are not taken into account. These effects become more consequential if the embankment dam is constructed in narrow valleys with materials of rather high permeability in the side abutments and when careful design and construction quality are not met, regarding the side watertight elements (e.g., grouting curtains, cut-off walls). Therefore, the effect and amount of affecting factors on side seepage results are of assistance for design engineers to have a better understanding of steady state seepage analysis.

Effect of Variation in Grouting Curtain Permeability

In narrow valleys, the major part of the water flow conveys through side abutments, especially if having a high coefficient of permeability, thus, the construction of grouting curtains with proper quality can reduce water flow through the side abutments significantly. Usually there are uncertainties regarding the desired coefficient of permeability of grouting curtain systems, as a result of improper construction techniques.

In this case study, the right abutment includes a 56 m deep layer of $1.3 \times 10^{\ 5}$ m/sec permeability underlain by a layer with a much lower permeability coefficient of $2.6 \times 10^{\ 7}$ m/sec. Figure 14 illustrates the variation of discharge rates from various downstream parts, with respect to changes in the ratio of the permeability coefficient of the right abutment grouting curtain to that of right abutment material. The most significant effect is on the downstream shell, where the widthwise flow lines from the side abutments mostly arrive. There is a 7 times increase in downstream discharge rate from 113.6 to 795.1 m^3/day as the permeability ratio increased from the initial value of $7.69 \times 10^{\ 4}$ to 1, representing a 1300 times increase. The exit flux from the left bank shows an increase from 21.3 to 60.3 m^3/day as the permeability ratio increases. This can be attributed to redistribution of the flow net and its effect on the downstream left bank discharge rate when the material properties change. It is believed that this change occurs in narrow valleys and, when the ratio of the crest length to the dam height increases, this effect will vanish. The total downstream discharge rate increases from 676.9 to 2320.9 m^3/day, a 3.4 times increase, according to the aforementioned change in the permeability ratio. Figure 15 shows the changes of water level in the downstream shell, according to changes in the permeability of the right grouting curtain. Changes of water level in percent form are depicted in Figure 16, indicating that, for 2, 10, 100 and 1300 (representing the permeability ratio of 1) times increase in grouting curtain permeability, there is 8.8, 24.6, 71.4 and 97 percent increase, respectively, in the downstream shell water level. Figure 17 shows the variation of the downstream toe hydraulic gradient with the permeability coefficient and represents a 2.23 times increase in gradient from 0.117 to 0.261 when the grouting permeability varies from $1 \times 10^{\ 8}$ to $1.3 \times 10^{\ 5}$ m/sec, a 1300 times increase.

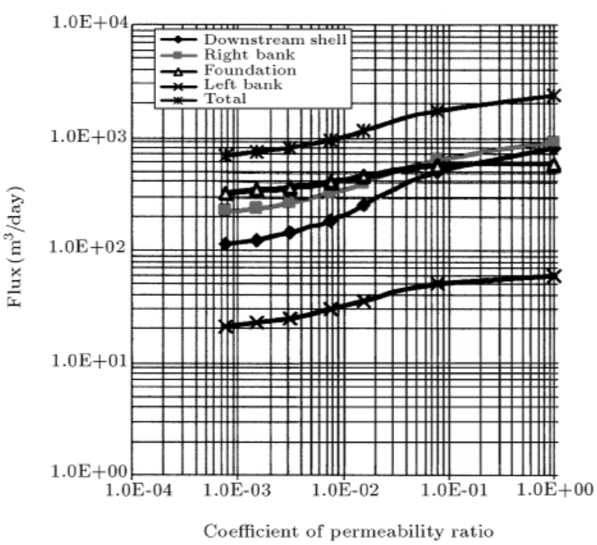

Figure 14. Variation of discharge rate with grouting coefficient of permeability of right abutment grouting curtain.

Effect of Depth Variation of Side Watertight Elements

The effect of the depth variation of the side grouting curtain on downstream seepage results was investigated and depicted in Figures 18 to 20. Figure 18 shows that increasing the depth of the right abutment grout

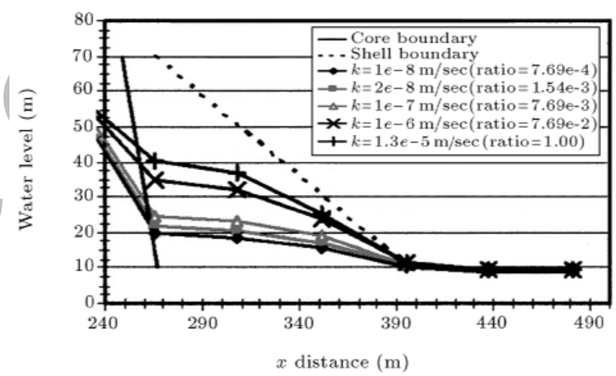

Figure 15. Variation of water level with grouting coefficient of permeability of right abutment grouting curtain.

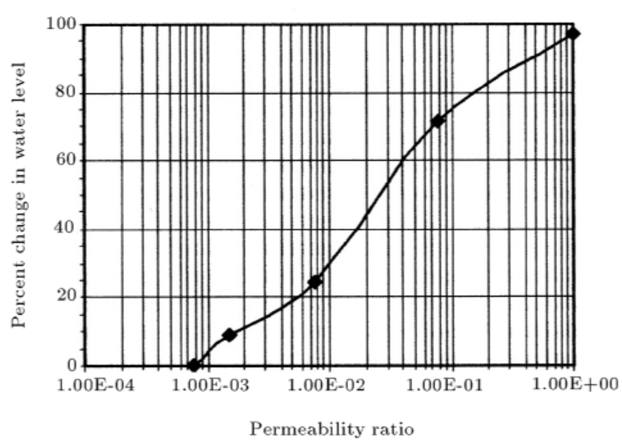

Figure 16. Variation of percent change in water level with permeability ratio of right abutment grouting curtain.

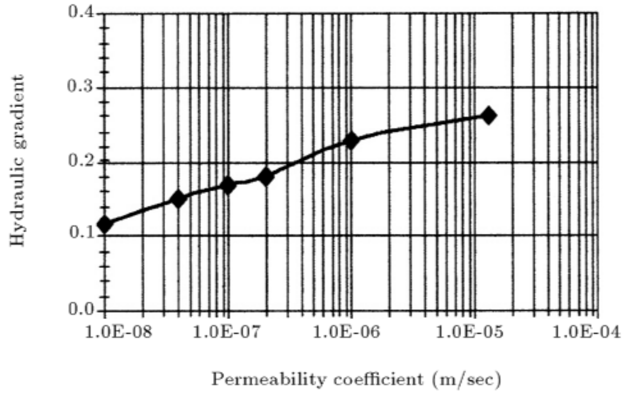

Figure 17. Variation of downstream toe gradient with grouting coefficient of permeability.

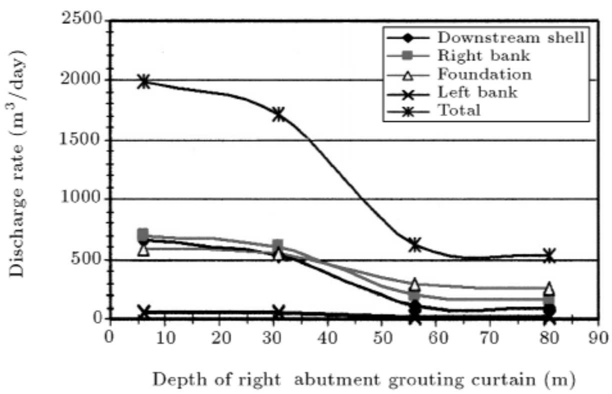

Figure 18. Variation of discharge rate with grouting curtain depth.

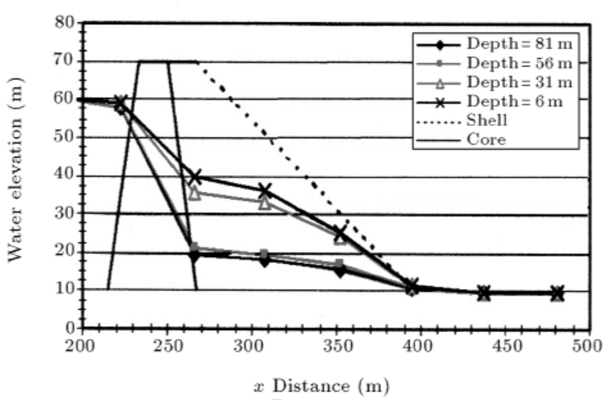

Figure 19. Variation of water level with grouting curtain depth.

curtain within the upper 56 m depth permeable layer does not have a considerable effect on the downstream discharge rates. However, the flux decreases significantly as the curtain moves into the layer of lower permeability, after which, increasing the right grouting curtain depth has little impact on the flux exiting from the right bank.

Figure 19 shows the changes of the water surface in the downstream shell, with respect to the depth of the right abutment grouting curtain. Like the flux rate, the sudden change in phreatic surface is obvious as the grouting depth reaches the low permeable layer. Figure 20 reveals the variation of hydraulic gradient at the downstream toe with respect to the grouting depth. There is no significant reduction in gradient magnitude until the grouting curtain passes the high permeable layer into the layer with lower permeability. Afterwards, increasing the grouting depth has an inconsequential impact on the magnitude of the downstream toe gradients.

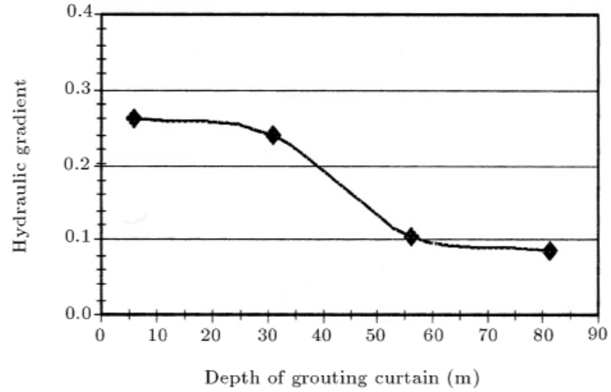

Figure 20. Variation of downstream toe gradient with grouting curtain depth.

CONCLUSIONS

In this paper, the effect of the third dimension on several steady state seepage problems in earth dams was investigated. For this purpose, the geotechnical and topographical conditions of the Chakoo Dam site as a real case study, were considered. In the first section, a comparison between two and three-dimensional steady state seepage analyses was implemented, indicating that, due to widthwise flows from the side abutments, the real water surface in the downstream shell stands at a higher position than that obtained from the two-dimensional analysis. The values obtained from the considered case study represented an increase of 35 percent in the water surface obtained from the 3D seepage analysis results. The three-dimensional hydraulic gradient showed a much greater value compared to the gradient obtained from the conventional two-dimensional analysis.

In the second part, the feasibility of the 3D modeling of the faults located at the dam site was investigated and the effect of the grouting treatment on the abutments and dam foundation, with different depths, was examined. A curve showing the reduction percent of the downstream discharge rate versus the treatment depth was presented.

Finally, the variation of seepage analysis parameters, i.e., water surface, discharge rate and hydraulic gradients; with some affecting factors from the side abutments, like soil permeability and grouting curtain depth that were not possible in the two-dimensional method, were studied. The results show that the effects of the material properties and grouting curtains on the downstream water level and discharge rates are much greater than on downstream hydraulic gradients. Also, it was illustrated that variation of the grouting curtain depth within a layer will not result in a significant change in water flux, phreatic surface and the hydraulic gradients until it is entered into the layer with a lower permeability coefficient, after which, there is a sudden change in the seepage results. Various curves obtained from the analyses lead to better understanding of the real steady seepage phenomenon reducing some uncertainties in the results when performing a conventional 2D analysis.

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