TECHNICAL NOTE

GYPSUM DISSOLUTION EFFECTS ON THE PERFORMANCE OF A LARGE DAM

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Abstract   Upper Gotvand dam is constructed on the Karun River located in the south west of Iran. In this paper, 2D and 3D models of the dam together with the foundation and abutments were constructed and several seepage analyses were carried out. Then the gypsum veins scattered throughout the foundation ground and also the seepage pattern were included in the models, hence the dissolution law of gypsum, was analyzed. It was disclosed that, the discharge fluxes obtained from 2D and 3D analyses are not similar and the discharge flux in 3D model is about 4 times the size of 2D model. Also, the 3D model localizes the phreatic surface some what higher than the 2D model does. This means that the 2D model estimates lower pore water pressure pattern in comparison with the 3D model. These may be attributed to the fact that with 2D model the lateral components of vectors of seepage velocity are ignored. In spite of the fact that the grout curtain is designed to be some 170 meters deep, however, complete dissolving of gypsum will severely increase the discharge flux through the foundation ground.

Keywords   Gypsum, Earth Fill Dam, 3D Seepage Analysis, Permeability

چکیده   سد گتوند علیا بر روی رودخانه کارون در جنوب غربی ایران واقع شده است. در این مقاله، مدل دوبعدی و سه‌بعدی این سد، پی و تکیه‌گاه‌ها ایجاد شده و تحلیل‌های تراوش متعددی بر روی آنها صورت گرفت. سپس رگه‌های ژیپس موجود در پی آغاجاری به مدل اضافه شد و الگوی زهاب، با درنظرگرفتن قانون انحلال ژیپس تحلیل گردید. هدف از این بررسی تعیین الگوی تراوش از پی سد و مقایسه آن با حالتی است که رگه‌های ژیپس از مدل حذف شده باشد. نتیجه تحلیل ها حاکی از تفاوت فاحش دبی خروجی از سد در مدل دوبعدی و سه‌بعدی می‌باشد. بطور کلی دبی خروجی از سد در مدل سه‌بعدی حدود ۴ برابر بیشتر از مدل دوبعدی می‌گردد. موقعیت سطح آزاد جریان آب در مدل سه‌بعدی بالاتر از موقعیت خط آزاد جریان آب در مدل دوبعدی به دست می‌آید. به عبارتی فشارهای منفذی در مدل دوبعدی کمتر از فشارهای منفذی در مدل سه‌بعدی است. با وجود پرده آب بند به عمق تا ۱۷۰ متر، پیش بینی می‌شود که در صورت انحلال کامل ژیپس دبی خروجی از سد بطور چشم گیری افزایش یابد.

1. INTRODUCTION

It is estimated that gypsum or anhydrite deposits underlie approximately 25 % of the earth surface. Only 10 % of these deposits outcrop. At these outcrops, or where gypsum or anhydrite strata occur in depths of a few hundred meters, gypsum karst has formed. Therefore extensive areas of gypsum karst exist world wide [1,2]. Some of the problems caused by the dissolution of gypsum and anhydrite in a dam construction site would be such as: gradual increase of seepage rate through dam abutments and foundation ground, dam breakage because of intensive leakage through foundations, reservoir loss due to intensive seepage through large leakage paths, strength reduction in foundation because of the gypsum dissolution, and concrete structures destroy because of the sulfated water caused by dissolution of gypsum and anhydrite. Saint Francis and San Fernando in

California State of the USA are two examples of the damaged dams due to the gypsum and anhydrite erosion. One of the countermeasures to such problems is to perform seepage analysis on a realistic model of embankment together with the foundation and abutments. Although the three dimensional analysis is an appropriate tool for these cases, its application to earth dams is rather complicated. Accordingly in engineering practice in order to estimate the seepage rate usually one or more critical sections are chosen and analyzed two-dimensionally. Generally, the two dimensional analysis, especially in narrow valleys or valleys with varying profile, is erratic. The main reason is that the lateral component of seepage velocity that is ignored in 2D approach may be quite considerable. As the Massingir dam had a uniform section in 3 km length, with a simple three-dimensional seepage analysis, more realistic results were obtained compared to two dimensional analyses and importance of three-dimensional seepage analysis was indicated [3].

If the two-dimensional flow equation is expanded to include the third direction, the three-dimensional flow equation is derived which is called coupled equation of flow. For an unsaturated soil having heterogeneous, anisotropic conditions, the coefficient of permeability at a point varies in the x, y, and z directions. But, the permeability variations in the three dimensions are assumed to be governed by the same permeability function. Continuity for three-dimensional, steady-state flow can be as follows [4]:

$$\left(\frac{\partial v_{wx}}{\partial x} + \frac{\partial v_{wy}}{\partial y} + \frac{\partial v_{wz}}{\partial z} \right) dx\, dy\, dz = 0 \qquad (1)$$

Where v_{wx}, v_{wy} and v_{wz} are water flow rate across a unit area of the soil in the x, y and z directions, respectively. Referring to Equation 1, the governing differential equation for the steady state seepage analysis in 3D space may be derived as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z} \right) + Q = 0 \quad (2)$$

Where k_x, k_y, k_z are the coefficients of permeability in the x, y and z directions, respectively; H is the total head; and Q is the flux at the model boundaries. Using the Galerkin principle of weighted residuals the finite element formulation for steady state seepage in three dimensions is derived as [5]:

$$\int_V ([B]^T [C][B])\, dv\, \{H\} = \int A(q\langle N \rangle^T \langle N \rangle)\, dA \qquad (3)$$

Where [B] and [C] are gradient matrix and element hydraulic permeability matrix, respectively. {H} is the vector of nodal heads and A is the area of the face of the element. q Is the unit flux across the faces of an element and $\langle N \rangle$ shows the vector of interpolating functions.

There are several geotechnical and geo-environmental problems involve seepage through soils. However, the coefficient of permeability is the most important parameter that dominates the water flow pattern through the soils [6]. It has been shown that in the steady state seepage problems the results obtained by using a typical permeability function may be quite close to those of exact solution [7].

Figure 1, represents the coefficient of permeability as a function of pore water pressure. Assume that for the first iteration all elements are assigned a saturated permeability (k_a) corresponding to zero pressure.

The flow made with this permeability will be more than the amount required and will result in a highly negative pore water pressure (point P_f). For the next iteration, the permeability will be k_f. This value does not allow for enough flow and the computed pressures will be positive. Once again, the permeability will be set to a value that is too
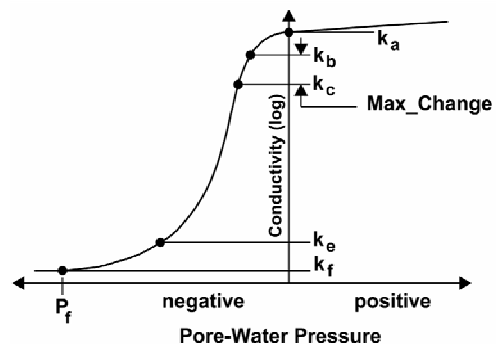

Figure 1. The general hydraulic permeability functions of materials.

high, resulting in a solution which oscillates between the extremities permitted by the function [5]. However, this figure clearly indicates the importance of application of a pressure dependent permeability function for both saturated and unsaturated zones of an earth dam. In this way such a zoning procedure will result in more accurate seepage flux than the case in which a constant hydraulic permeability function is used [7]. Using a constant permeability value may result in erratic results. Phreatic surface position may be unrealistic and flow rate in unsaturated zone may be extremely high. When using a constant permeability value, water can flow through unsaturated zone like that of saturated zone [5]. Hydraulic permeability values of the embankment can be measured from field and lab tests such as Lugeon test and there are several methods introduced in different references.

2. THE UPPER GOTVAND DAM PROJECT

The dam is constructed across the Karun River, in the Khuzestan province of Iran, north of Shushtar city. It is a 178 m high earth dam with central clay core. The dam is underlain by the Bakhtiari Formation (BK) overlying the Aghajari Formation (AJ). While the BK formation remains in its horizontal position, the AJ formation is folded and faulted, the bedding planes and joints are inclined with varying dip angles.

Apertures within the Bakhtiari formation are usually vertical and have relatively large openings and continuity of the apertures often reaches to several meters [8]. In Figure 2, geological layers of Upper Gotvand dam are depicted. The AJ-rocks contain veins of gypsum usually associated with clay stone beds. The maximum thickness of the veins is reported to be 2 cm and even wider that appear as thin films on the beddings and along joint planes. The latter ones were formed subsequently and indicate the dissolution of gypsum and re-sedimentation in the joints. In general, gypsum is encountered below 25 m deep. Inspecting foundation borehole logs of the AJ formation at the dam site, 4 different depths were observed in which gypsum veins exist. These are summarized in Table 1.
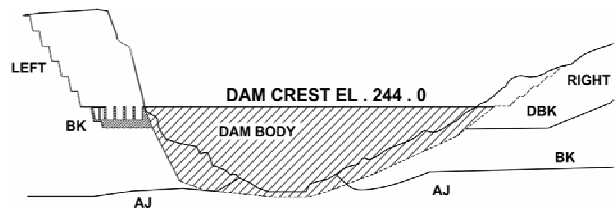
Figure 2. Upper Gotvand dam geological sections; AJ = Aghajari formation, BK = Bakhtiari formation, DBK = dislocated Bakhtiari formation.

TABLE 1. Levels Containing Gypsum Veins in the Upper Gotvand Dam Foundation.

| Layers	Gypsum Levels in Foundation (m)	Aperture Average Spacing (m)
Mass 1	- 20 ~ - 45	10
Mass 2	- 55 ~ - 65	25
Mass 3	- 70 ~ - 80	35
Mass 4	- 90 ~ - 170	45

3. MODELING

The Seep 3D soft ware was employed as an effective tool for seepage analysis. Seep3D is a new software product for modeling three-dimensional seepage problems. Seep3D is formulated for conditions of constant total stress; that is, there is no loading or unloading of the soil mass.

It is assumed that the pore-air pressure remains constant at atmospheric pressure during transient processes [5]. This software use finite element method for seepage analysis and it is able to consider unsaturated condition. This software contains three elements hexahedron, prism and tetrahedron for modeling as shown in Figure 3a.

In order to establish an appropriate model for seepage analysis, following steps were taken:

3.1. Geometry In order to create the geometry of the model, topographic maps of the dam site and also section drawings at the distances of 50 m were used; also the hexagonal element in Seep3D software was employed (Figure 3).

(a)

(b)

(c)
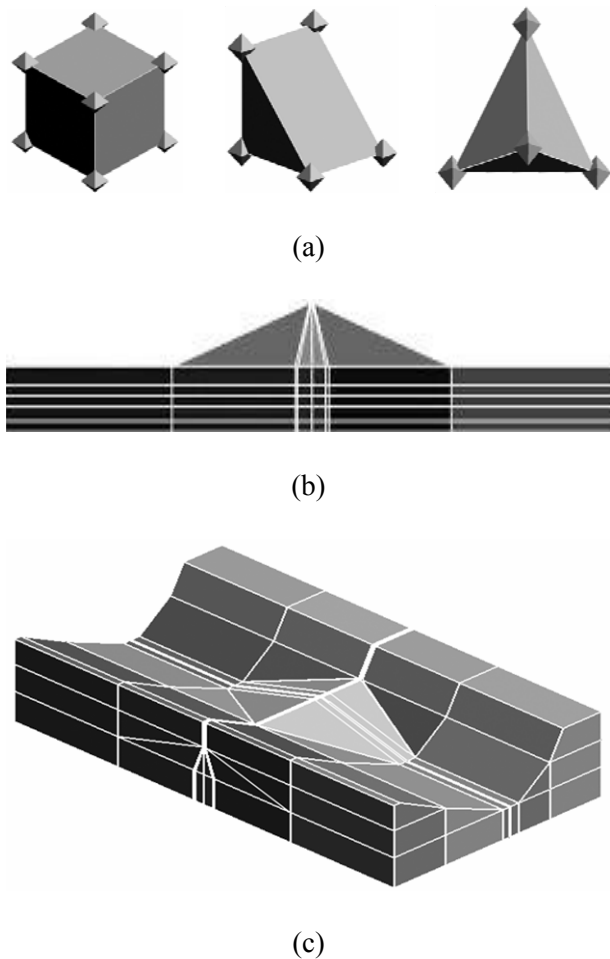
Figure 3. (a) Hex, prism and tetra elements in seep 3D; (b) 2D model; (c) 3D model of the upper Gotvand dam.

There are two boundary conditions in steady state seepage analysis. The maximum water level in the reservoir was considered as the upstream boundary surface. For down stream, potential seepage condition was applied. In other words, all surfaces that water may seepage through were considered as potential seepage surfaces.

It is common in finite element method to model the dam with the adjacent zones including reservoir, abutments and foundation. Since the required extend of the boundary in the foundation ground is not known, it is necessary to carry out some boundary sensitivity analyses. However, for 3D analysis, an overall mass of 200 m in depth and 300 m in width (abutments) was obtained to be quite satisfactory.

3.2. Material Properties The embankment material and foundation ground engineering properties were introduced as follows; for the embankment materials the laboratory permeability test results at zero pressure were used to establish the general permeability functions. These functions are shown in Figure 4.

Compacted soil behaves transversally isotropic in which, $k_x = k_y \neq k_z$. Generally with earth dams it may be accepted that [5,9]: $k_x/k_y = 1$ and $k_x/k_z = 10$.

For foundation ground, some considerable numbers of Lugeon permeability test results are available. These results were averaged and used to categorize the foundation ground layers in terms of permeability. However, it should be noted that the foundation ground was considered hydraulically isotropic, i.e.: $k_x = k_y = k_z$.

In Table 2 results of Lugeon test results at Aghajari formation in foundation ground are presented. These results are from exploratory boreholes in dam foundation ground. Regarding this table the weighed average Lugeon value is estimated to be 6 Lu, which is equal to about 9×10^{-7} m/s.

Trial grouting in Aghajari formation showed that cement grout could not satisfactorily penetrate into the gypsum veins [8].

3.3. Sensitivity Analyses of 2D and 3D Models for the Number of Elements In order to select the appropriate finite element mesh, sensitivity analyses for the number of elements were carried out for both 2D and 3D models. The results are shown in the Figures 5, 6.

It can be seen that increasing the number of elements in the 2D model, decreases the discharge flux; hence the appropriate number of elements for 2D analysis is some 17000 elements. For 3D model results converge at about 25000 elements, however. Therefore, in seepage analysis with 3D model convincing results can be achieved by increasing the mesh to 32000 elements and finer.

3.4. Modeling of Gypsum Veins in Foundation Ground Gypsum is hardly soluble in water, but with water temperature and pressure raise its solubility increases [10]. Water flowing through narrow fissures and fractures in soluble rock, such as limestone and gypsum, widens these
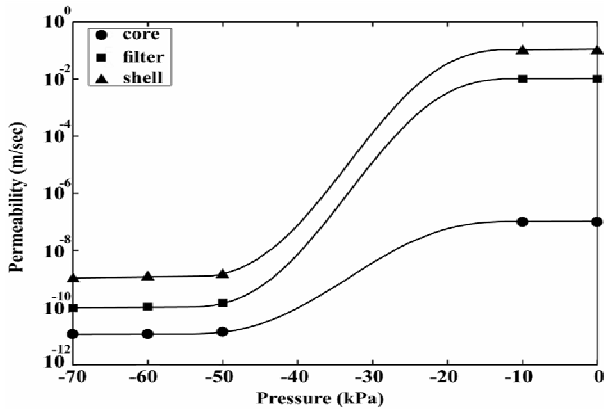
Figure 4. Permeability functions of the upper Gotvand dam.

Figure 5. Number of elements-discharge flux relation in 2D model.

TABLE 2. Lugeon Test Results Abundance Distribution.

Lugeon	Total Test Length (m)
0 ~ 1	290
5 ~ 7.5	86
7.5 ~ 15	5
15 ~ 25	10
25 ~ 35	5
100	29
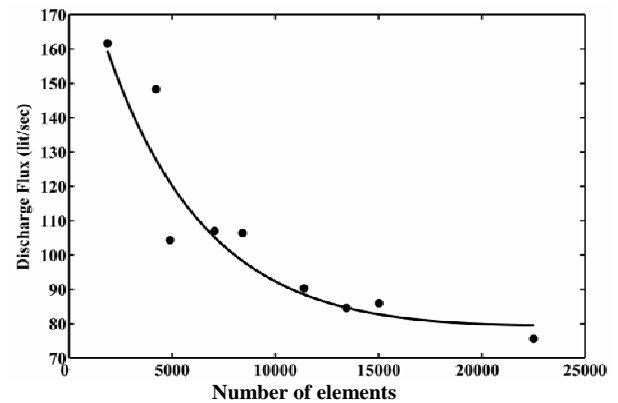
Figure 6. Number of elements-discharge flux relation in 2D model.

by chemical dissolution.

Recent modeling approaches on two-dimensional domains of dam sites have shown that under unfavorable conditions leakage below dam sites can increase to an unbearable extent within the lifetime of the structure [11].

In case of flowing water, dissolution phenomenon continues until the gypsum has been washed away completely leaving wider apertures and open fractures. In order to model mode of formation and performance of these apertures, the following hypothesis was used. According to Figure 7 and Equation 4, equivalent permeability for the supposed rock mass can be computed as bellow [12]:
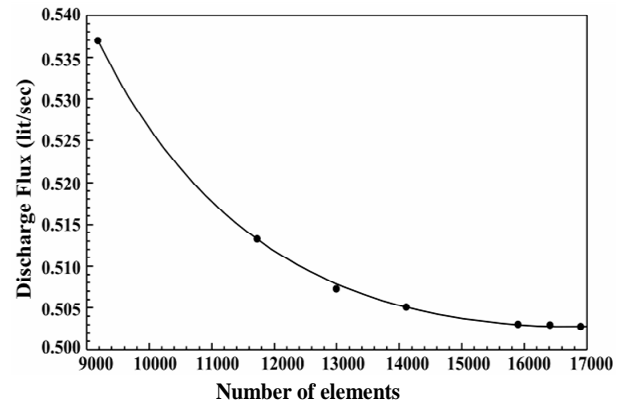
$$k = \frac{\rho g}{12\eta} \frac{a_0^3}{s} \tag{4}$$

Where ρ = density of water; η = viscosity of water and equals 0.0065 at 25˚C; g = acceleration due to gravity; a_0 = aperture width; and s = fractures average spacing.
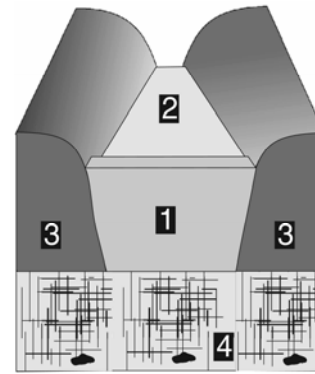
In Table 1, Gypsum veins are classified into 4 general depths. Generally water flow through fractures is either laminar or turbulent flow. In the early stage, there is laminar flow through apertures and dissolution is faster at the aperture entrance. As the calcium concentration in pore water increases, the rate of dissolution of gypsum reduces and a funnel-like conduit evolves there. This opening at the exit enhances the flow rate through the fracture, and therefore, the funnel-like opening at the entrance propagates further downstream, and also

the dissolution rates at the exit increase further. By this time the water flow becomes turbulent and now the flow rate is so high that the concentration of calcium becomes close to zero and dissolution rate tends to be even along the fracture. Therefore as time proceeds, the funnel-like shape becomes smoothened out [12]. Figure 8 shows the variations of the Aghajari formation mass permeability against aperture width. This figure reveals that dissolution of gypsum veins increase the mass equivalent permeability up to 75 ~ 300 times depending on aperture width and spacing.
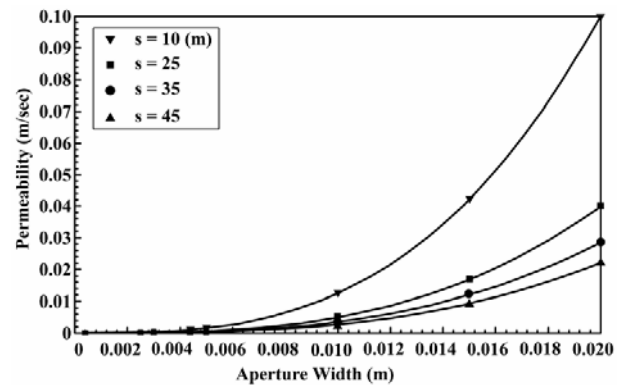

Figure 7. Gypsum veins modeling; (1) Embankment; (2) Reservoir; (3) Abutments; (4) Fracture network.

4. RESULTS AND DISCUSSION

4.1. Aghajari Formation Permeability   As mentioned formerly, the weighed average Lugeon value of Aghajari formation is estimated to be 6 Lu, which is equivalent to about 9×10^{-7} m/s. Figure 8 shows the variations of this formation permeability against aperture width. Referring to this figure it is revealed that the dissolution of gypsum veins increase the mass equivalent permeability up to 75 ~ 300 times depending on aperture width and spacing. This much increase in permeability advocates the potential hazards of gypsum veins.

4.2. Discharge Flux Inspection   In Figures 6, 9, the results of 3D analyses of discharge flux through the dam foundation are shown. In Figure 6 the dissolution of gypsum is ignored and the discharge flux is estimated to be 0.075 m³/s. in 1 m of dam length. However, in Figure 9 it is supposed that the gypsum veins finally are washed away and a passage for seepage flow is evolved. According to this figure the rate of increase of discharge flux due to dissolution of gypsum veins was obtained to be a third order function of the aperture width. Comparing these figures the dominant effect of dissolution of gypsum on discharge flux is disclosed. It is seen that as the aperture width reaches to 2 cm due to gypsum dissolution the discharge flux increases about 240 times. Results of the same analyses with 2D model are shown in Figures 5, 11. Referring to Figure 5 and considering dam length the initial discharge flux is estimated to be 0.025 m³/s.

**Figure 8**. Variations of equivalent rock mass permeability against aperture width for different aperture spacing.

Comparing Figures 5 and 11, reveals that with 2D modeling the discharge flux increase due to gypsum dissolution is estimated to be some 360 times.

Figure 10 shows the results of variations of discharge flux against the changes of aperture width from 0.04 to 2 cm for 3D model. Similar analysis was carried out for the 2D model (typical section) and the results are depicted in Figure 11. Although the grout curtain is designed to be some 170 meters deep, however, complete dissolve of gypsum will severely increase the discharge flux through the foundation ground. As is shown in Figure 10, with 3D model as the aperture width increases up to 2 cm, the discharge flux rises to 18 m³/s., while with 2D model discharge flux rises to
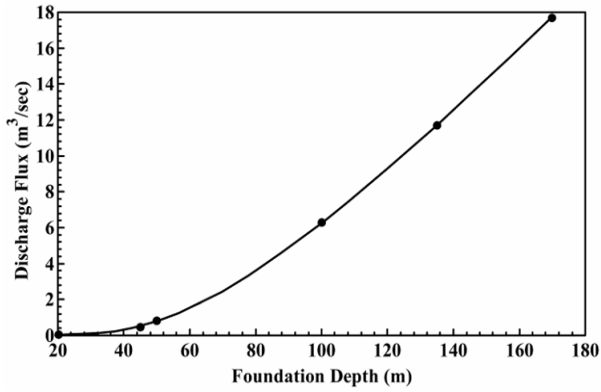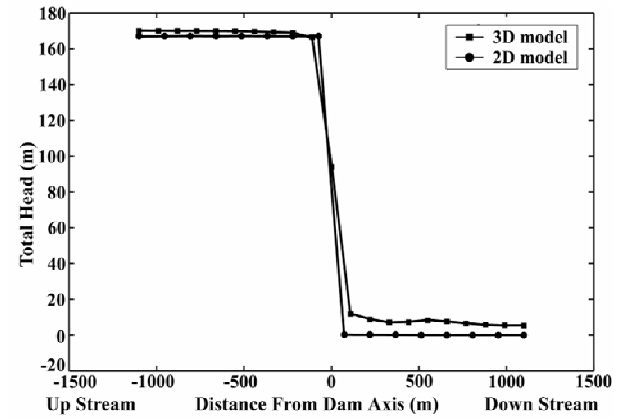
Figure 9 Discharge flux changes against gypsum layer depth in 3D model ($a_0 = 2$ cm).
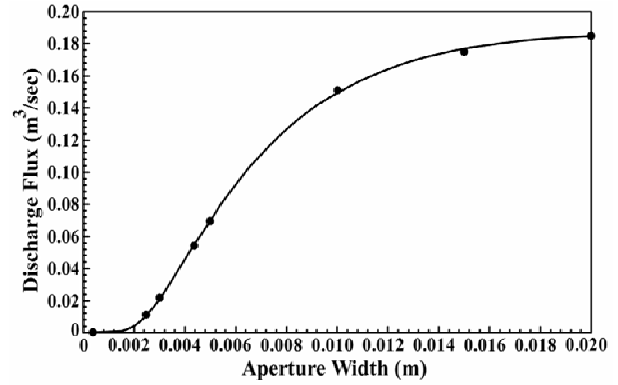
Figure 11. Discharge flux changes with respect to the aperture width change in typical section of the 2D model.
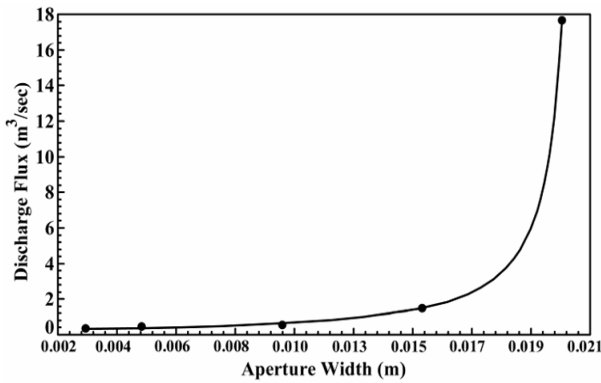
Figure 10. Discharge flux changes against aperture width in 3D model.

Figure 12. Phreatic surface location with 2D and 3D models.

about 0.018 m³/s./m. For whole dam length this will be 9.0 m³/s. These figures indicate that the discharge flux with 3D model is about 2.0 folds that of 2D model. However, referring to Figures 5 and 6 this ratio would be about 4 if the gypsum dissolution effect is ignored.

These differences between the results of 2D and 3D approaches may be attributed to the fact that, with 2D seepage analysis the flow net is planer indeed and lateral components of seepage velocity are ignored, so the flow necessarily passes through the successive sections with different permeability. Thus discharge flux is dominated by the sections with lower permeability. With 3D seepage analysis, however, flow is 3D and water follows routs with lower energy dissipation producing

higher discharge flux which is realistic.

4.3. Pore Pressure Inspection   In order to study the pore water pressure pattern in the embankment and foundation ground, the phreatic water surface through the dam was located using both 2D and 3D models. The results are plotted in Figure 12. It is seen that the 3D model locates the phreatic surface some what higher than the 2D model does. This means that the 2D model estimates lower pore water pressure pattern in comparison with the 3D model. This may be attributed to the fact that with the 2D model the lateral components of the seepage velocity vectors are ignored. It is noted that in this part of work the

effects of dissolution of gypsum is not taken into account.

5. CONCLUSIONS

In this paper the seepage behavior of Gotvand dam considering effects of dissolution of gypsum is evaluated with both 2D and 3D models. Some eminent concluding points are as follows:

- The 3D analysis estimates the discharge flux about 2.0 ~ 4 times that of 2D analysis.
- The 3D model locates the phreatic surface some what upper than the 2D model does. This means that the 2D model estimates lower pore water pressure pattern in comparison with the 3D model.
- Dissolution of gypsum veins of Aghajari formation increase the mass equivalent permeability up to 75 ~ 300 times depending on aperture width and spacing (Figure 8); and the rate of increase of discharge flux in Gotvand dam, due to dissolution of gypsum veins, is a third order function of the aperture width.
- According to 3D and 2D approaches, the initial discharge fluxes are 0.075 m^3/s. and 0.025 m^3/s. respectively. However, it is estimated that the gypsum dissolution will increase these figures to about 18 m^3/s., 240 times, and 9 m^3/s., 360 times, respectively.
- Considering potential hazards of Gypsum veins in foundation ground either deep plastic concrete cut-off wall or a longitudinal gallery for casual grouting in future is recommended.

6. REFERENCES

1. Jeschke, A. A., Vosbeck, K. and Dreybrodt, W., "Surface Controlled Dissolution Rates of Gypsum in Aqueous Solutions Exhibit Nonlinear Dissolution Kinetics", *Elsevier Science Ltd.*, Vol. 65, No. 1, (2001), 27-34.
2. Ford, D. C. and Williams P. W., "Karst geomorphology and hydrology", Unwin Hyman, London, U.K., (1989), 1-3.
3. Serafim, J. L., Santos, A. P. and Matos, M. S., "Tridimensional Seepage through A Dam Foundation", *Proceeding International Committee on Large Dams*, Lausanne, Switzerland, (1985).
4. Fredlund, D. G. and Rahardjo, H., "Soil Mechanics for Unsaturated Soils", John Wiley and Sons, New York, U.S.A., (1993), 150-177.
5. GEO-SLOPE International Ltd., Seep3D Software, "Seep3D user's Guide", Version 1.1. Alberta: Calgary, (2002).
6. Sadrekarimi, J. and Saghafi, M., "Stress Dependent Permeability Effects on Ground Water Flow", *Amir Kabir Journal of Science and Technology*, Vol. 4, No. 53, (2003), 35-42.
7. Freeze, R. A., "Influence of the Unsaturated flow Domain on Seepage through Earth Dams", *Water Resources Reaserch*, Vol. 7, No. 4, (1971), 929-942.
8. Mahab Ghods Consulting Engineers, "Report of International Expert Panel on Upper Gotvand Dam and HEPP", Mahab Ghods Consulting Engineers, Tehran, Iran, (2005), 7-25.
9. Fell, R., Mac Gregor, P. and Stapledon, D., "Geotechnical Engineering of Embankment Dams", Balkema, Rotterdam, Netherlands, (1992), 202-210.
10. Blyth, F. G. H. and De Freitas, M. H., "A Geology for Engineers", Arnold, London, U.K., (1984), 87-88.
11. Romanov, D., Gabrovsek, F. and Dreybrodt, W., "Leakage Below Dam Sites in Limestone Terrains by Enhanced Karstification: A Modeling Approach", *Journal of Environmental Geology*, Vol. 51, No. 5, (2007), 775-779.
12. Romanov, D., Gabrovsek, F. and Dreybrodt, W., "Dam Sites in Soluble Rocks: A Model of Increasing Leakage by Dissolutional Widening of Fractures Beneath a Dam", *Journal of Engineering Geology*, Vol. 70, (2003), 17-35.