SEEPAGE IN THE WEATHERED FOUNDATION OF ABSHINEH DAM (IRAN), PART I: THE EFFICIENCY OF ONE LINE GROUTING

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ABSTRACT
Abshineh dam is an earth fill dam with a clay core in which a complicated seepage has appeared through its foundation. Insufficient geotechnical investigation, the highly weathered rock of foundation, the inadequate depth of cut-off wall, and a fault and a Qanat* running in to the foundation are made the foundation's leakage more serious. Also, the one line grouting, which has been applied as a sealing method, is evaluated; the outcomes prove that a high rate of erosion has been occurred in the dam's foundation, and *the efficiency of one-line grouting in the foundation of Abshineh dam is not enough to make it watertight.*

RÉSUMÉ
Le barrage d' Abshineh est un barrage en remblai avec un noyau d'argile dans lequel une fuite est apparue au niveau des fondations. Une reconnaissance géotechnique insuffisante, la forte altération du substratum, la profondeur du rideau imperméable trop réduite, une faille et un qanât* dans les fondations du barrage rendent la fuite dangereuse. L'injection en line utilisée comme moyen d'étanchéité est évaluée. On montre que les fondations du barrage sont marquées par un fort taux d'érosion et insuffisamment rendues imperméables par l'injection pratiquée.

1. INTRODUCTION

Abshineh dam is a clay core dam located in western part of Iran, Hamedan province, on the Abshineh River and downstream from Ekbatan dam. The satellite image presenting the location of Abshineh dam is shown in Figure 1. The Abshineh dam was constructed in 1996 to provide the water for drinking and irrigation purposes. Moreover, the discharged water of Ekbatan dam accumulates behind Abshineh dam. Table 1 presents the main characteristics of the Abshineh dam.

Figure 1. The satellite image of the location of Abshineh dam

Table 1. The main characteristics of Abshineh dam

	Abshineh Dam Characteristics	
1	Maximum height of dam	18 m
2	Abshineh dam's crest level	MSL+1818
3	Maximum water level	MSL+1818
4	Normal water level	MSL+1815
5	Crest length	660 m
6	Crest width	8 m
7	Normal reservoir capacity	5,000,000 m^3
8	Area of reservoir	750,000 m^2
9	Length of reservoir	1200 m

Figure 2 shows a typical cross section of Abshineh dam, which is comprised by three main parts: rock fills, filters, and a clay core. The double filter at the downstream side is used to prevent piping or transportation of clay particles from the core into the rock-fill zone. It is important to notice that an appropriate design of filter and its material size can effectively prevent piping through the dam's body. Also, a cut-off wall with a constant depth of two meters had been designed; yet, because of the different depth of constructed cut-off wall, varying from 0.35 to 2 meters; it is not included in this figure (Figure 2), neither in the seepage analysis. However, in a weathered rock foundation like Abshineh dam's, a well designed and well constructed cut-off wall is an important element which can change the underground flow path, and comprehensively prevent piping through the foundation.

*Qanat is a continued underground aqueduct (small tunnel without lining) which was invited in Persia and used to transit water from mountains to flat areas. Also, vertical shafts with equal distances were used to access to Qanat and dredge it. More information can be found on www.Qanat.info

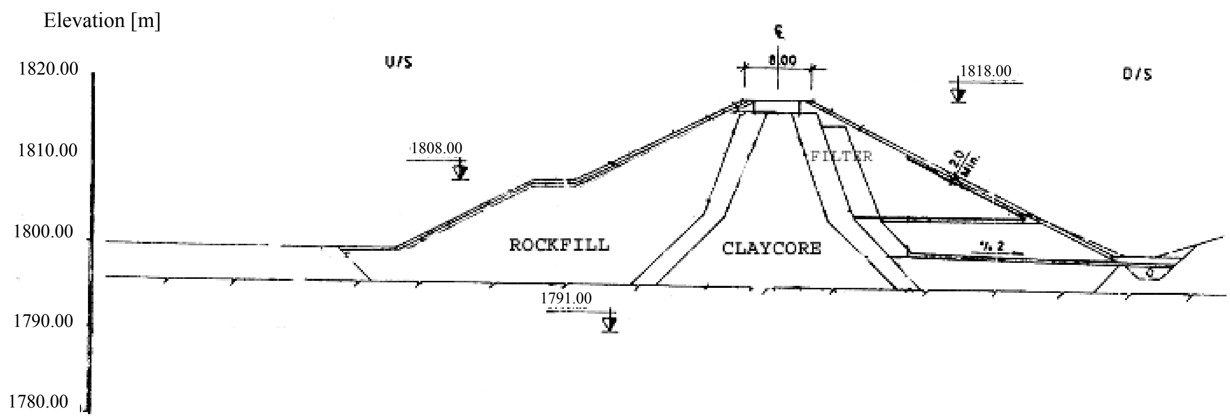

Figure 2. Typical cross section of Abshineh dam (because of the different depth of constructed cut-off wall, varying from 0.35 to 2 meters; the cut-off wall is not included in this figure, neither in the seepage analysis

Figure 3 represents a plan view of the Abshineh dam which its right embankment is extended to provide a higher reservoir capacity. In addition, the concrete structure[1], being used to discharge reservoir water, is displayed. Letters which are accompanied with numbers over the crest of the dam (C38, C37…) signify primary holes (with distance of 16 meters) in an effort to get the foundation watertight; also, secondary and tertiary holes are presented by circles; some of them, however, are not grouted.

The interest is focused on the foundation of this dam: a complex site, both from the geological point and geotechnical matter. For instance, the combination of karstic limestone and silt in the highly weathered foundation are clearly an indicator of a potential seepage problem; under this condition, the seepage can wash out the clay and silt particles through the limestone fissures and develop piping.

It is not possible here to elaborate on the design process of Abshineh dam, but it is important to mention that this project has a lack of basic investigation; only one exploration borehole was drilled at the dam's location which presented a weathered rock as it is illustrated in Figure 4 (Mahab Ghodss, 1996). In fact, this case is a clear example that the underground condition cannot be guesstimated, and geotechnical examinations are a very important part of the design process of infrastructures (ICOLD, 2005). Accordingly, the Qanat and fault which cross through the foundation of Abshineh dam were not considered in the design phase.

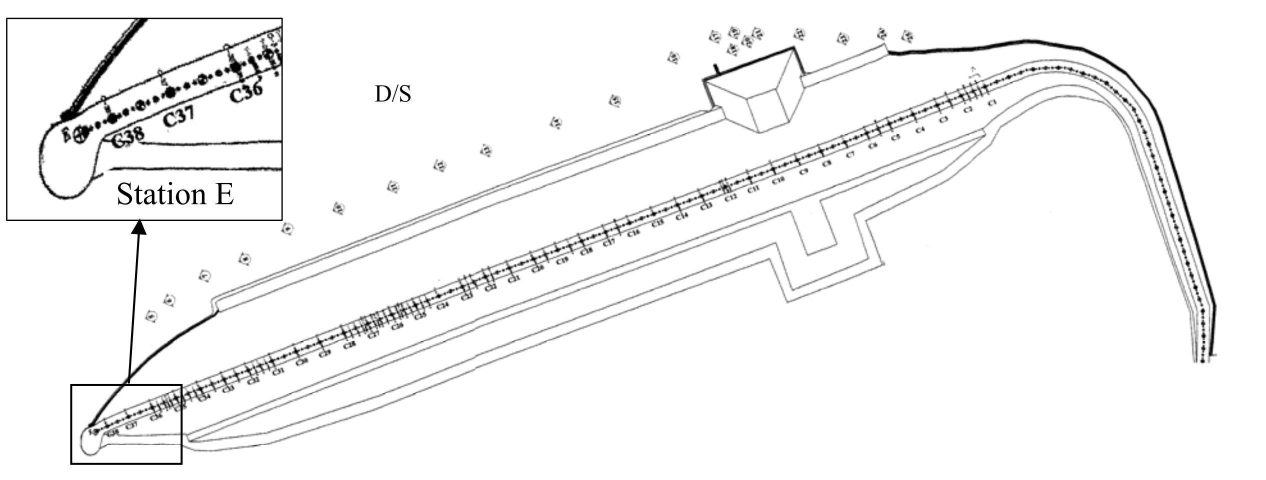

Figure 3. Plan view of Abshineh dam; station E, is located on the left bank where the Abshineh dam is started (The total length and width of Abshineh dam's crest are 660m and 8 m, respectively)

[1] Because of the probability of piping, it is suggested avoiding design of a (concrete) structure passing through the clay core; and, in the case of Abshineh dam regarding the highly weathered foundation, presence of the structure means an unacceptable risk of piping.

Figure 4. The cores of the borehole which are bored at the dam axis, from left to right (Mahab Ghodss, 1996)

2. DAM SITE GEOLOGY

The site of Abshineh dam is located at Sanandaj-Sirjan[2] zone, expanding overall the northeast of Hamadan province, Iran. The valley of Abshineh dam is almost symmetrical; the left abutment has a slope of around 4.5%, and the right abutment has a slope of 13.6% below MSL+1818 and 3.3% above that level.

The formations of the dam's foundation are a composite of shale, marl-shale and sand-shale followed by layers of lime sand-stone with medium sand size; and, the main composite is marl-shale. The mineral compounds of the main bedrock is marl-shale, clay-silicate, quartz, and carbonate substances. In addition, some metal minerals such as Fe_2O_3 can be found in the field. Shale is highly weathered, and sandstone layers are relatively in better situation (Mahab Ghodss, 1996).

The in-situ data of boring, testing, and grouting displays a highly cracked zone within 2 to 3 meters depth under the base of Abshineh dam, and its uniaxial strength is close to 12 MPa. Medium and high weathered rocks are at a depth of 2-6 meters below the base. And, in deeper places the uniaxial strength reaches up to 32 MPa or more.

3. HISTORY OF PROBLEMS AND SOLUTIONS

During the construction of Abshineh dam, a high rate of water flow passing through the foundation was detected when the rain water accumulated behind Abshineh dam could easily flow through the foundation; therefore the consultant company suggested one-line grouting a curing pattern for the foundation; therefore, to evaluate the performance of one line grouting pattern in the foundation of Abshineh dam, a grouting test was proposed and applied in a limited region (6 meters length!) over the half-constructed clay core (when the height of the dam was maximum 5m from its base).

The grouting test was applied at 0+430m from station E, located in the left abutment as shown in Figure 3. After grouting test it was concluded that:

- The permeability of clay core is acceptable,
- the contact zone (the area between clay core and the foundation) has a permeability of 10^{-4} cm/s,
- The highest permeable zone was under the cut-off wall, and
- Grouted cement decreased permeability of the foundation (Mahab Ghodss,1995).

Then, one-line grouting along the top of the crest in permeable areas of foundation was suggested as a remedial plan, in which at first the distance between boreholes was 16 m, and it could reduced to 2 meters in the more permeable zones. In this manner, the permeable boreholes were grouted, and the low permeable ones were filled with cement.

After first impounding in 1996, seepage was observed at the downstream side, and so was grouting restarted in the areas that had not been grouted before (low permeable boreholes). Once more, at second impounding in 1999 when the height of impounded water was 6 meters, water flow was observed at three locations of downstream side: right, center, and left; the downstream side of the Abshineh dam was totally wet. The rate of discharges flowing over the downstream were estimated 20 lit/s at the right side and almost 4 lit/s at the left side; yet, the seepage rate in central part was low. In fact, Abshineh dam was intently faced with internal erosion; and, in as much as it might cause instability of the dam, the impounding was interrupted, reservoir water completely

Figure 5. Boring a vertical shaft over the crest, C1 crossed the fault through the foundation

[2] Sanandaj-Sirjan is one of the most seismic zones of Iran; and, this zone has registered diverse phases of magmatism, metamorphism and deformation. More information about this zone can be found in: http://www.ngdir.ir/States/

discharged (in a dry season), and the grouting seriously restarted.

In this time, even grouting more than 7.5 tons cement in C1, a borehole at the right abutment of dam, could not fill it up; so was a shaft with diameter of 70 cm bored from the crest, and the excavation exposed a fault under the foundation. Figure 5 shows a picture taken from inside of the fault. Therefore, to make this fault sealed, a masonry-wall in one-meter thickness was created, and then it was grouted with a mixture of the cement and bentonite. As far as, there is a serious doubt about the efficiency of this approach, the seepage has been separately analyzed, and the consequences of this wall on the surrounding are evaluated.

Meanwhile, boreholes C11, C12, C13, C14, C27, and C34 intersected with cavities under the concrete cut-off wall; these cavities clearly show the karstic nature of the foundation. In addition, close to left abutment, borehole C27 crossed an old Qanat; the same approach, which was used to close C1, also, applied to make it sealed.

4. MODELING

4.1 Basic Assumptions

Seepage of Abshineh dam has been analyzed using SEEP2D, a two dimensional (2D) finite element program. Nevertheless, using a two dimensional program provides some restrictions and limitations; to overcome these limitations, the dam body and its foundation are divided into different zones by length, and each zone is modeled separately and average soil properties of each zone are applied to the model; totally, eight zones are defined. As a result, the total seepage of Abshineh dam is estimated by summing up of the seepage volume of all of the zones. In addition, the analyses have been done for two reservoir water levels: 1809 and 1818 which represent the water level of existing data and full supply level, respectively.

Figure 6 shows the basic model used for seepage analysis of Abshineh dam. The main elements constructing the model are a clay core, grout curtain, weathered rock, and fresh rock. The cut-off wall, with varying depth, and rock-fills are not included in the model.

4.2 Elements of the Model

The grout curtain, being a zone with lower permeability, is modeled by low permeable elements, and its permeability and thickness is estimated by using the information of grouted boreholes and several checking boreholes.

Furthermore, the Qanat which passes through the foundation of Abshineh dam is modeled separately. It is modeled like a small underground tunnel which the head of water, passing through this canal, is equal to the reservoir head. This assumption comes from the site conditions where the surface rock is highly weathered and several vertical shaft had been created to access to the Qanat. Figure 9-10 present the results of the analyses of

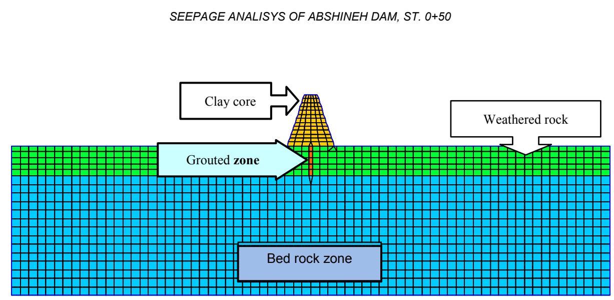

Figure 6. Abshineh dam model used for seepage analysis in SEEP2D

the full reservoir water level. In this case, the outcomes of the analyses have been used for evaluation of the sealing approach used to make the Qanat and fault which cross through the foundation of Abshineh dam watertight.

4.3 Available Data

The data which are used for updating the model can be divided into two categories: the data of drilling boreholes including in-situ testing and grouting, and the piezometric data. The first group of data, in this case, is used as a basic source of information for modeling, and the second group is used for controlling and updating the model.

In other words, the average of in-situ testing and grouting data in each zone defines the permeability of the clay core, weathered rock, fresh rock, and grouted area. Therefore, this is a practical modeling that is completely based on the in-situ data. Meanwhile, the piezometric data can effectively help updating the model.

Any piezometer, moreover, can act like an alarm warning the internal erosion or increasing seepage flow. Unfortunately, at the first impounding of Abshineh dam, no pizometer was installed; although, it had been designed. Later on, at the second impounding in 1999 several piezometers were installed in three typical areas: clay core, contact zone, and foundation rock to measure local pore pressures.

5. RESULTS

As it is previously explained, in order to utilize a two dimensional finite element program, the dam body and its foundation are divided to eight zones, and the average properties of each zone is applied to each model.

5.1 The 1st Zone

The first zone, is the first 40 meters of dam's length from left bank (station E), where the height of clay core is zero, as it is depicted in figure 3. However, there are no data to calibrate model for this zone; yet, the high permeability of primary borehole C34 and flowing water at the downstream side after grouting of neighborhood signifies high permeability of this zone.

5.2 The 2nd Zone

In the second zone, including primary boreholes, C35, C36, and several intermediate holes, no grouting was done before first impounding. Yet, after the impounding and observation of seepage flow at the downstream side, this zone was completely grouted. Analyses of data coming from boreholes, in-situ testing, and grouting manifest both of the maximum velocity and total volume of seepage have been reduced by grouting. Table 2 presents the results of the seepage's analyses before and after grouting; and on the base of these results the efficiency of grouting is estimated near 65% for seepage reduction. Meanwhile, the area of high velocity seepage has been decreased after grouting as it is shown in Figure 7-8 which is important to get the probability of piping in a weathered foundation reduced.

Table 2. Results of the seepage analysis before and after grouting in the second zone

MSL+	Before grouting		After grouting	
	Seepage (lit/day)	Max. velocity (m/day)	Seepage (lit/day)	Max. velocity (m/day)
1809	430	0.092	143	0.026
1815	1436	0.031	480	0.089

5.3 The 3rd Zone

Primary boreholes of the *third zone* had divulged a very low permeability before impounding. However, the piezometric data addressed a higher permeability after impounding. In fact, back analyses of seepage proved that erosion has been occurred in the foundation of Abshineh dam. In order to find the rate of erosion, different value of permeability was tested as the input data. A brief of this process is summed up in Table 3. The outcomes show a higher permeability which is almost 5.5 times more than the permeability before impounding (for duration of near two years) which proves a high rate of erosion.

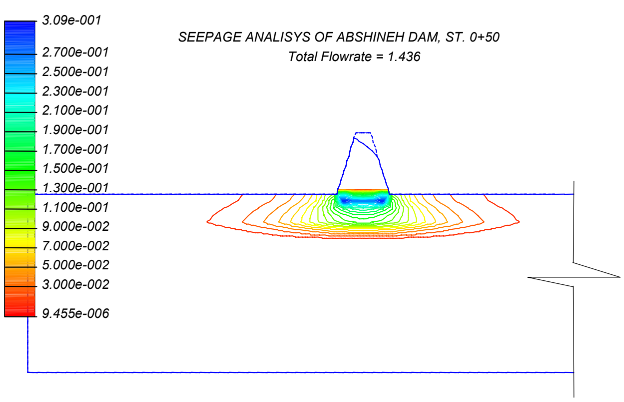

Figure 7. The velocity contours of seepage before the grouting in the foundation of Abshineh dam (in m/day)

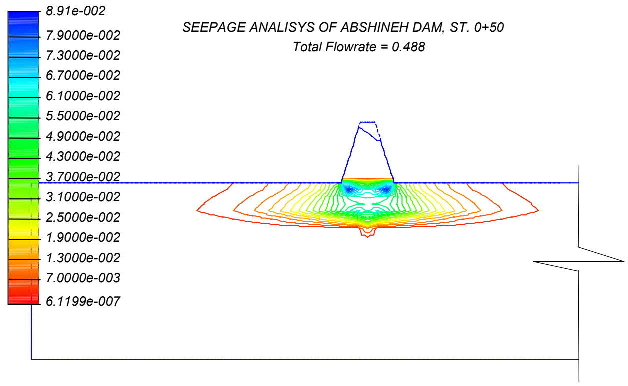

Figure 8. The velocity contours of seepage after the grouting in the foundation of Abshineh dam (in m/day)

Table 3. To get equivalent pore pressure (water-level), backward analysis has been done with the assumed permeability.

MSL+	Piezometer A4		Piezometer A5	
1809	measured water level	calculated water level	measured water level	calculated water level
1ST	70.1807	1805.4	1802	1802.5
2ND	70.1807	1807.63	1802	1800.75
3RD	70.1807	1807.17	1802	1801.67

5.4 The 4th Zone

In the fourth zone, half of the drilled holes disclosed a permeability of near 10^{-3} cm/s during in-situ testing; a big deal of cement was grouted in this zone. For instance, even grouting of 7.5 tones of cement could not fill the primary hole, C27; an old Qanat was found in this zone by excavating the borehole over the crest.

To seal this Qanat, a masonry wall (combination of rock and cement) in one-meter thickness was created; then, it was grouted by the mixture of cement and bentonite. This, also, had been used for closing the fault which was crossed with C1 (see figure 5). In order to check the performance of this approach and its effects on surrounded areas, a separate modeling is done. Fig 9-10 present the results of seepage's analyzing used for it. The base of modeling, also, has been explained on the section of modeling. As shown in the figure 9, a concentration of high velocity seepage which is spread beneath the contact layer is an undesirable consequence of this approach; in other words, developing of piping in the contact layer is seriously encouraged.

Also, Figure 9 which presents the co-potential contours expresses if piping starts no sign can be seen on downstream side, because the Qanat acts like a drainage tunnel; so this closing approach not only does not provide a permanent remedial method but also needs more instrumentations to monitor the erosion!

Table 4. The calculated rate and volume of seepage for different zones of Abshineh dam in MSL+1818

Zone number	Start of zone	End of zone	Primary Boreholes	Piezometers (* Later added)	Max. Velocity (cm/day)	Seepage (lit/m/day)	Seepage (lit/day)
1	0+0 (station E)	0+40	----		---	---	---
2	0+40	0+60	C29 to C36		8.90	480	9600
3	0+ 60	0+170	C26 to C33	A1u, A1d, A2, A4, A5	1.76	93	10,230
4	0+170	0+230	C24 to C28		4.69	247	14,820
5	0+230	0+410		A7u, A7d, A10, A11	4.68	316	56,880
6	0+410	0+585	C2 to C12	A13u, A13d, A14	2.10	121	21,175
7	0+585	0+600	C1		9.47	865	12,975
8	0+600	0+678		A21u, A21d, Ab10*	---	---	---
Total calculated seepage from Abshineh dam and foundation							125,680

5.5 The 5th Zone

Like in the third zone, none of the holes had been grouted before the first impounding in the fifth zone because of a very low permeability divulged by the drilling and in-situ tests; and, after impounding, the out flow of water at the downstream side showed a higher permeability. Piezometers of this zone, named A7d and A10, had data which were analyzed, and the results proved a high rate of erosion occurred after impounding. As a matter of fact, the back analysis demonstrates that by assuminig $K_x = K_y = 10^{-4}$ cm/s, the pore pressure is in agreement with the data of piezometers which do very well correspond with each other. This, also, confirms the analyses results of the other zones and proves the erosion-able nature of the Abshineh dam's foundation. Accordingly, three important cases can be concluded:

- *No grouting is made a high rate of erosion possible in the* foundation of Abshineh dam.
- A high rate of erosion is expected in the whole length of weathered foundation of Abshineh dam.
- A high probability of piping in the contact layer[3] is expected.

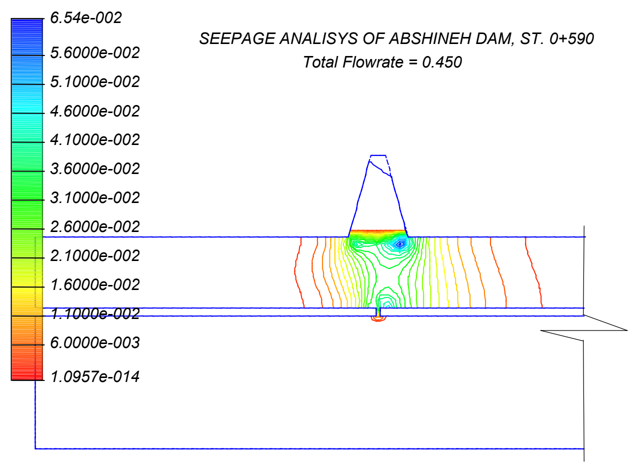

Figure 9. The velocity contours of seepage flow, and the evaluation of sealing approach applied on the Qanat passing through the Abshineh dam's foundation (in m/day)

5.6 The 6th Zone

The sixth zone spreads over 75m along the dam axis whereas the last 30 meters is on the right abutment. Also, this zone, included primary boreholes C2 to C12, was reported a low permeable area before impounding. Yet, back analyses of pyrometers' data, named A13u, A13d, and A14, with an updated model demonstrated internal erosion in the foundation.

5.7 The 7th Zone

The seventh zone contains primary borehole C1, having a permeability of more than 100 Lugeon[4] over its full length.

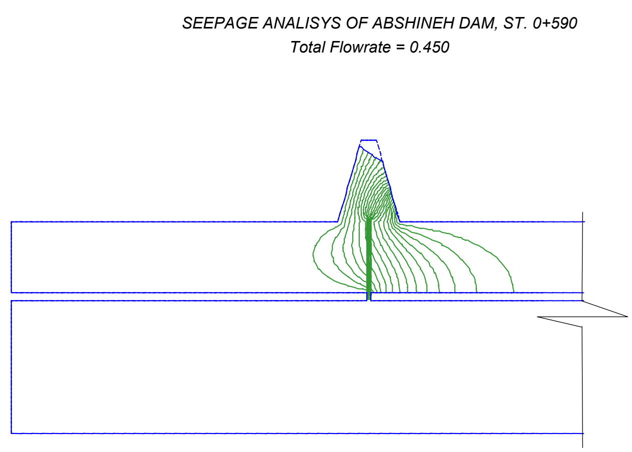

Figure 10. The pressure contours of seepage flow, and the evaluation of sealing approach applied on the Qanat passing through the foundation of Abshineh dam.

[3] Contact layer is the area where the clay core connects with the foundation.
[4] 1 Lugeon unit = 1 litre/m/minute at 150 psi (or 1034 KPa).

This borehole intersected a fault crossing the Abshineh dam through its foundation. This fault, also, was sealed in the same approach as the Qanat; so can analyses of Qanat (see Figure 9-10) also be applied for this it.

5.8 The 8th Zone

There is a lack of data in this zone. However, some piezometers have been installed, yet the fault can act like a drainage tunnel for this zone; it easily affects on the piezometric data.

6. THE EFFICIENCY OF GROUTING CURTAIN

In order to theoretically estimate the efficiency of one line grouting at the general condition of Abshineh dam's foundation, the simplified version of Dachler equation (Dachler, 1963) has been used (Casagrande, 1961). The parameters of this equation are: D, the depth of alluvial layer; d, an equivalent depth of fully grouted zone; and W=D-d, the total depth of open spaces included n openings. In other words, d/D is the cut off ratio, and W/D is the open space ratio.

Cut-off efficiency $E_C = \frac{q - q_C}{q}$, and for W/D < 0.1

$$Ec = \frac{\log_{10} \frac{2D}{\pi W}}{\frac{n}{2.93} \cdot \frac{B}{D} + \log_{10} \frac{2D}{\pi W}}$$

A brief of sensitive analyses of the simplified Dachler equation for the efficiency of grout curtain of Abshineh dam is presented in Table 5. Also, on the base of the field observation the hatched cells of the Table 5 can be chosen as the (overestimated) matching values. In other words the maximum efficiency of the grout curtain is estimated near 60 percent. These values, also, certify the obtained results by the finite element method which is, for instance, presented in Table 2.

Table 5. The estimated efficiency of grouting curtain by simplified Dachler's equation, it is assumed the value of W=0.001 for the left table and W=0.01 for the right table

	n	E_C
1	50	0.69
2	100	0.52
3	150	0.42
4	200	0.36

	n	E_C
1	50	0.62
2	100	0.45
3	150	0.35
4	200	0.26

In fact, the real condition of Abshineh dam's foundation which a Qanat and a fault intersect it, has a karstic nature, and a high rate of erosion occurred by seepage (5.5 times more permeability within about two years) will make the grouting curtain less efficient than the computed values.

In this case, the most important point for the engineer is that they do not rely on a design which its maximum efficiency at beginning is near 60% on the optimum situation of the site. Casagrande, however, believed that the maximum efficiency of one-line grouting was not more than 30% according to his experience (Casagrande, 1961).

Besides, it should be considered that there are some zones which one-line grouting system is not efficient like the Qanat, fault, or the karstic zones which are estimated totally being near 24% of the dam's length. In this case, the fault tree analysis of failure of one-line grouting system, presented in Figure 12, shows a combination of different failure modes. By analysis of this fault tree, the probability of failure of one-line grouting system in the foundation of Abshineh dam is estimated 51%.

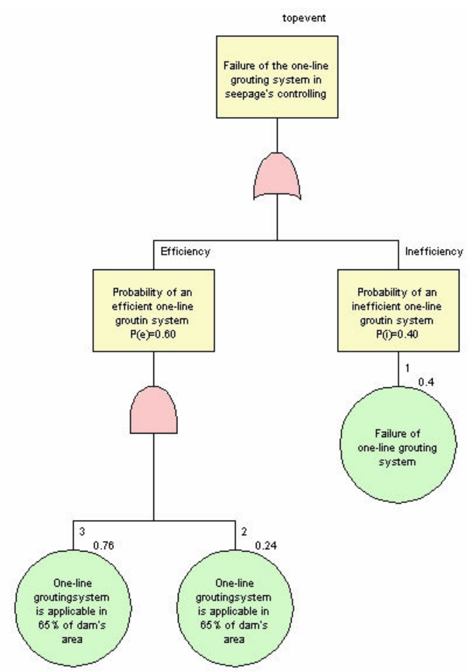

Figure 11. The fault tree for assessment of failure of one line grouting system in the foundation of Abshineh dam (in OPEN FTA).

7. CONCLUSIONS

The efficiency of one-line grouting in the foundation of Abshineh dam is not enough to make the foundation watertight; its (optimistic) efficiency is estimated near 50%. Casagrande, however, believed that the maximum efficiency of one-line grouting was not more than 30% according to his experience (Casagrande, 1961).

Bearing in mind several case studies which suffer from one line grouting system (Casagrande, 1961; Seed, 1987; Popovichi, 1999), it is reconfirmed that the performance of the one-line grouting system is not as much as engineers can rely on it as the only system for seepage's controlling.

The in-situ and piezometric data prove that a high rate of erosion has been occurred in the foundation of Abshineh dam. For instance, the average permeability of the third zone has been increased almost 5.5 times for about two years.

The analyses of method used to seal the Qanat or fault show that the contact layer in those areas are seriously encountered to a high probability of erosion which will cause piping. The piping, in this case, would have flowed toward the underground drainage (see Figure 10); therefore, realizing of piping in those areas needs an accurate monitoring system.

Since concentration of seepage with higher velocity occurs in the grouted zones; so the one-line grouting does not provide a permanent remedial method.

8. RECOMMENDATIONS

It is recommended that engineers do not rely on the one-line grouting system as the only system for seepage's controlling.

Evaluation of the reliability of one line grouting is a practical research topic for dam engineers.

9. ACKNOWLEDGMENT

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