A Numerical Modeling Study for Determining the Optimal Depth of Grout Curtain in Foundation and Abutments of Karun 4 Dam

M. Hosseini[1*], S. Sazandeh[1]
1- Department of Mining, Imam Khomeini International University, Iran

* Corresponding Author: *meh_hosseini18@yahoo.com*

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Abstract

Some experimental relations have been developed for determining the grout curtain depth, but these relations cannot be applied to any dam with any geological condition. Therefore, the effect of the grout curtain depth on seepage through foundation and abutments of each dam should be studied separately. To examine this parameter in Karun 4 dam, the numerical modeling method was applied using FLAC in a 2-dimensional modeling process. Permeability coefficient is an important parameter in numerical modeling. In this research, the experimental relationships for Lugeon values and permeability coefficient were used to determine the required permeability. A transverse section was used to model each of the abutments and the foundation of Karun 4 dam. The grout curtain was designed as a wall with a very low permeability at different depths. After modeling the grout curtain with various lengths, the curtain depth was determined based on seepage level, curtain flow efficiency, drilling-injection costs, and value of seepage water. The grout curtain depths were calculated to be 70, 184, and 104 at the foundation, left abutment, and right abutment, respectively. Also analysis of the pore water pressure and flow lines shows when the curtain is sewed to the Pabdeh Formation, we have the high efficiency in the grout curtain.

1. INTRODUCTION

Changes in the groundwater flow net and increased water pressure at abutments and foundation of dams after impounding are among the negative consequences of dam construction [1]. During the construction of dams, it is necessary to take various precautions in order to enable the impermeability and stability of the bed rock [2]. Seepage analysis and the control of groundwater in flows from fractured rock masses are significant problems in dam engineering [3,4].

Different methods including the construction of grout curtains are employed. Grout curtains have been used in the U.S. to control seepage in rock masses under and around dams of all types since the 1890's [5]. In the twenty first century, there are technologies, tools, and procedures available that permit designing and constructing grout curtains as the engineered elements of a water retaining structure. Prior to the 1980's, very little in the way of design was performed for foundation cutoffs. Grout curtain configurations and depths were determined by rules of thumb, often ignoring the site specific geologic conditions [6]. The contribution of a grout curtain to the reduction in discharge of seepage through abutments and foundation of the dam can be examined by preparing a model of each abutment and the dam foundation.

The methods for analyzing the water flow in soil are analytical and numerical solutions, electric analogs, hydraulic models and flow net illustration. Groundwater flow is usually studied with 2D models in porous environments [1].

To analyze and examine the seepage process using numerical methods, one of the important input parameters required is the rock mass permeability coefficient. This coefficient is typically obtained through in-situ experiments. The most well-known experiment of this kind is the water pressure test named Lugeon after its inventor. Lugeon value is converted into Darcy permeability coefficient to study seepage, using experimental relations [7].

The settlement at permeable abutments and foundation is controlled using a retaining wall with low permeability (such as a grout curtain). The most effective parameter on the seepage of a grout curtain is the penetration depth of the curtain. Therefore, in determining the optimal depth of the grout curtain, an extremely precise analysis is carried out to minimize seepage discharge. The grout curtain should reduce permeability considerably. Moreover, for the grout curtain to influence the flow net and drainage flow, its bed should reach less permeable layers so as to reduce the flow and slope of the output drainage drastically. The grout curtain is constructed to close and seal all of the routes with high permeability. Application of numerical analysis methods and the subsequent use of numerical software in large-scale construction projects have been common even in distant past, but there is not a long history of the use of these methods for modeling water flow in rock masses, especially at dam sites. In 1995, Naouss and Najjar studied chart-based calculation of seepage and obtained approximate values of seepage and gradient below hydraulic structures using the charts and the finite element numerical method. The hydraulic structures studied by these researchers included a steel pile, a dam with a grout curtain, and a dam without a grout curtain. Using the charts developed by these researchers, it is possible to calculate the permeable layer permeability, thickness of the permeable layer, and head loss based on the grout curtain permeability coefficient and length (if available) [8]. In 1997, Ewert studied permeability based on the site of dams and introduced experimental relations for the relationship between permeability and leakage discharge [9]. Sivakan (2005) also examined the relationship between leakage and permeability under a concrete dam and a steel pile [10]. It is difficult to analyze and control leakage discharge. This difficulty is the result of the diversity of rocks, unknown underground fractures, and variability of rock fracture degrees [11].

This research has attempted to study seepage at the foundation and abutments of Karun 4 Dam and determine the optimal depth of grout curtain for this dam based on the information obtained from permeability tests on the dam site and numerical analysis using FLAC2D.

2. KARUN 4 DAM

The site of Karun 4 Dam is situated in Chaharmahal and Bakhtiari Province, 185 km southwest of Shahr-e Kurd and 35 km southwest of Lordegan. It is located at the northern latitude of and the eastern longitude of $50° - 24' - 50''$. The Karun 4 Project consists of a reservoir dam and a ground power plant. It is a double-curvature arch dam with a height of 230m and a crown length of 337m. The dam foundation has an altitude of 802 and its crown has a height of 1032 m. The reservoir water level is 1025 under normal conditions, and the minimum altitude of water harvestable by the power plant is 990m. To generate electricity, a ground power plant (with a power generation capacity of 100 MW) is anticipated to be built on the left side of the dam on the bank of Manj River, and its product will be used at the dam. The water level at the basin is 945 m, with a discharge of 728 m3/sec using four turbines. Fig. 1 shows the geographical location of the dam site, and Fig. (2) depicts the positions of the injection galleries, groundwater level, basin level, the dam body and geological formation [12].

The geological formations around the site in the order of emergence are as follows: Khami group, Bangestan group, Gorpy, Pabdeh, Asmari, Gachsaran, Aqajari, and Bakhtiari. These formations are composed of limestone, limestone marl, marl, evaporite deposits, and conglomerates. To determine the physical and mechanical properties of the rock samples at the site of Karun 4 Dam, rock mechanics experiments were carried out on the samples obtained from the core of exploratory bores. Results of these tests are presented in Table 1.

3. CALCULATING THE PERMEABILITY COEFFICIENT USING LUGEON TEST

The rock masses on the site of Karun 4 dam consist of the Asmari and Pabdeh formations. The Asmari formation forms the upper part with a high permeability, while the Pabdeh formation is at a greater depth and has a low permeability. To assess rock permeability on the site of Karun 4 dam, experiments were conducted on on nine exploratory boreholes where,

- Boreholes on the right abutment were used to determine permeability at the Asmari formation: BH1, BH2
- River bed bores were used to determine permeability at the Asmari formation: BH6, BH7
- Boreholes on the left abutment were used to determine permeability at the Asmari formation: BH3, BH4, BH13
- Boreholes for assessing permeability at the Pabdeh formation: BH35, BH36

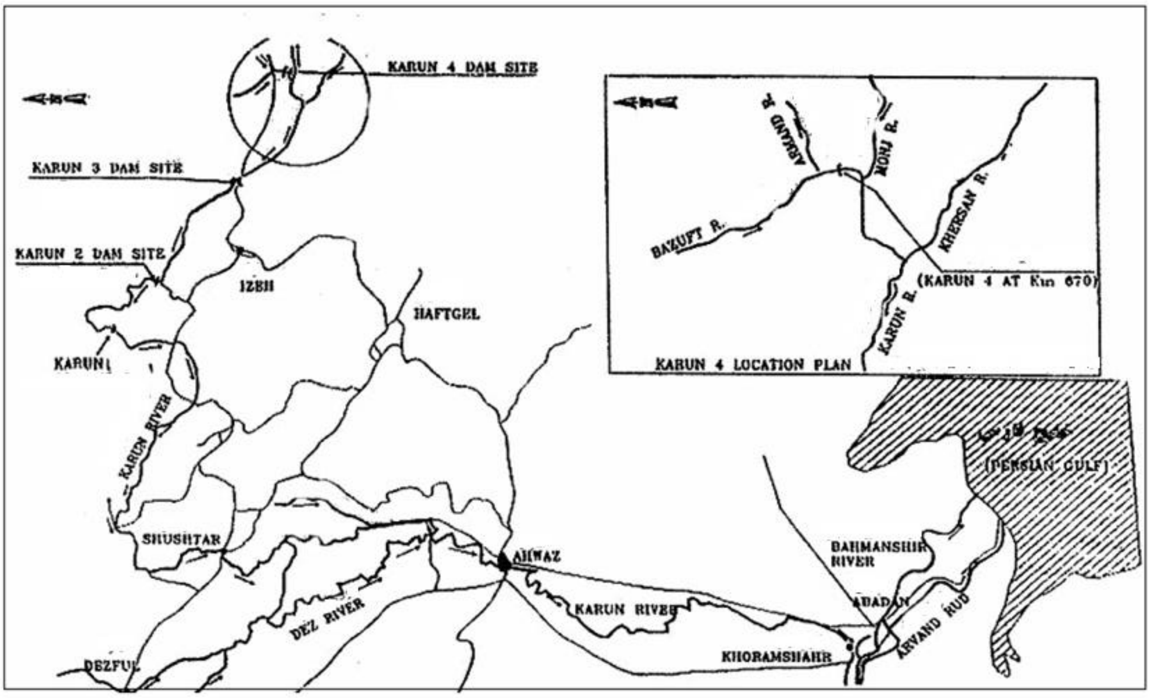


Figure 1. Geographical location Karun 4 Dam site [12]

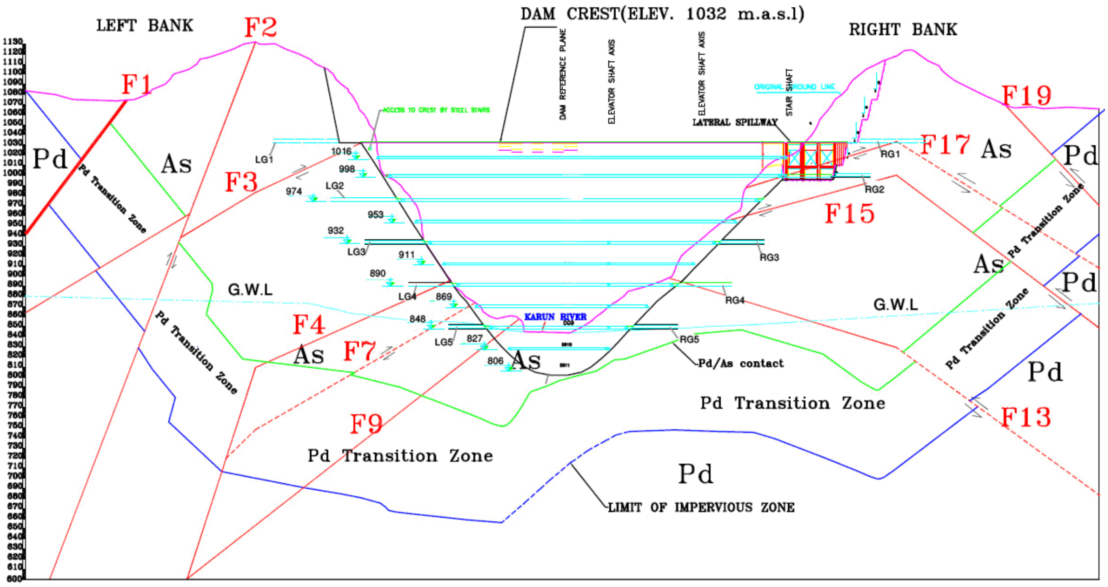


Figure 2. Location of the dam body, injection galleries, and geological formation at the site of Karun 4 Dam (Front view) [12]

The average Lugeon values for each abutment and the dam foundation are as follows at the Asmari and Pabdeh formations [14].

4. NUMERICAL ANALYSIS OF SEEPAGE AT THE FOUNDATION, RIGHT AND LEFT ABUTMENTS OF KARUN 4 DAM

To analyze seepage at the abutments and foundation of the dam using numerical methods, one of the important input parameters is the rock mass permeability coefficient. This coefficient was originally introduced by Darcy and was obtained through the Darcy test. Therefore, in seepage analysis, the Lugeon value is converted to Darcy permeability coefficient.

Table 1. Geomechanical parameters of rock mass on the site of Karun 4 dam [13]

Parameter	Limy marlstone	Porous limestone	Marly limestone	Limestone
Elastic modulus (GPa)	6	3	11	19
Poisson's ratio	0.28	0.32	0.25	0.2
Cohesion (MPa)	0.3	0.15	0.5	2
Density (ton/m^3)	2.49	2.36	2.54	2.63
Uniaxial compressive strength (MPa)	50.15	46.26	67.07	103.83
Tensile strength (MPa)	8.16	4.95	6.63	9.64
Internal friction angle (degree)	35	30	42	45

Table 2. Average Lugeon values at the site of Karun 4 Dam [14]

Location	average Lugeon values at the Asmari formation	average Lugeon values at the Pabdeh formation
right abutment	25	6
left abutment	47	6
foundation dam	48	6

According to Ewert, permeability coefficient around the section under study is calculated using Eq. (1) [9].

$$K_i = \frac{1.6 \times 10^{-5} \times Q_t}{2\pi \times r \times H} \qquad (1)$$

where:

K$_i$: Permeability coefficient (m/s), Q$_t$: Water absorption under the pressure of 1 bar at each test section ($lit/\min$), r: Bore radius (m), H: Test section length (m)

By extending Eq. (1), if the bore radius is 76 mm and the length of test sections is 5 m, there is a simple relationship between the Lugeon value and permeability coefficient [7].

$$K = 1.3 \times 10^{-5} \times Lu \qquad (2)$$

K: Permeability coefficient (cm/s), Lu: Lugeon value.

It is worth mentioning that in all models, the thickness of the grout curtain was 3m and a Lugeon value of 3 was assumed based on the sealing measure applied to the Karun 4 Dam.

To analyze seepage and water flow at the foundation and abutments of Karun 4 Dam, FLAC2D was used. This software is a finite difference program based on a Lagrangian computation method. Therefore, it is useful for modeling conditions caused by large deformations. The input parameters for FLAC are listed in Table (3) for each model [15].

Table 3. Input parameters in FLAC for modeling water flow

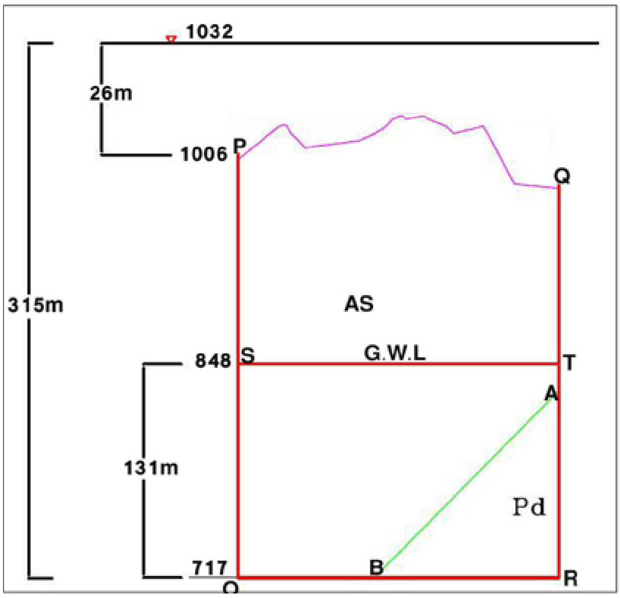
Parameter	Value	Unit
Density of rock	2630	kg/m^3
Bulk modulus of rock mass	10555.6	MPa
Shear modulus of rock mass	7916.61	MPa
Bulk modulus of grout curtain	22619	MPa
Shear modulus of grout curtain	11046.5	MPa
Density of grout curtain	2700	kg/m^3
Density of water	1000	kg/m^3
Bulk modulus of water	0.01	MPa
Gravitational acceleration	10	m/s^2

Since the permeability coefficient is expressed in m2/Pa s in FLAC, all of the permeability values should be converted to this unit. This value is obtained by dividing the permeability coefficient by the product of gravity acceleration and water density. All of the water parameters required by the software are presented in Table 3. FLAC is also developed with a powerful programming language called FISH. Using this language, a program was coded to calculate the input and output flows until equilibrium is obtained. In this paper, only the fluid flow was modeled in FLAC. It shall be noted that in the resulting model, fluid flow (i.e. flow of groundwater) travels through a permeable solid object. Flow modeling was independent of mechanical computations, so in this study, only the effects of the grout curtain on the changes in the flow lines and the distribution of the pore water pressure were discussed and contours of displacement were not presented.

The boundary conditions for groundwater are considered as steady pore pressure, and saturation is assumed to dominate the boundaries and then the steady phase fluid flow is modeled. For example, Fig. (3) depicts boundary and initial conditions in right abutment for the first phase.

To analyze settlement at the dam foundation, four different phases were assumed:

1- Phase 1: Modeling without a grout curtain
2- Phase 2: Modeling with a 32-meter deep grout curtain (length of 37 m) at dam foundation
3- Phase 3: Modeling with a 47-meter deep grout curtain (length of 54 m) at dam foundation
4- Phase 4: Modeling with a 70-meter deep grout curtain (length of 81 m) at dam foundation



initial pp $= 131\times 10^4$ var $0 - 131\times 10^4$ of OSTR for region Initial pore pressure

Pore pressure for boundary of OP apply pp $= 315\times 10^4$ var $0 - 289\times 10^4$

initial saturation $= 1$ Saturation condition for boundary of OP

initial saturation $= 1$ Saturation condition for region of OSTR

initial saturation $= 0$ Saturation condition for boundary of TQ

Figure 3. Boundary and initial conditions in right abutment for the first phase.

Results of numerical analysis of foundation settlements are presented in Table (4). The permeability status at the Asmari and Pabdeh formations, as well as the grout curtain are shown in Fig. 4. Figs. 5 and 6 also depict the seepage discharge curves for the first and fourth phases with steady inflows and outflows.

The thickness of the Asmari formation at the foundation is less than the abutments, resulting in less depth penetration of the curtain in the Pabdeh formation. In the third phase in comparison to the second, the increase in curtain length at the foundation is less than the abutment (because the Asmari formation has a lower thickness at the foundation). These analyses were aimed to examine the effect of curtain depth on water seepage.

Table 4. Final results of water flow modeling at foundation of Karun 4 dam

Model	Seepage discharge (m^3/s)
Phase one	4.42×10^{-4}
Phase two	3.08×10^{-4}
Phase three (grout curtain of Karun 4 dam)	2.30×10^{-4}
Phase four	9.26×10^{-5}

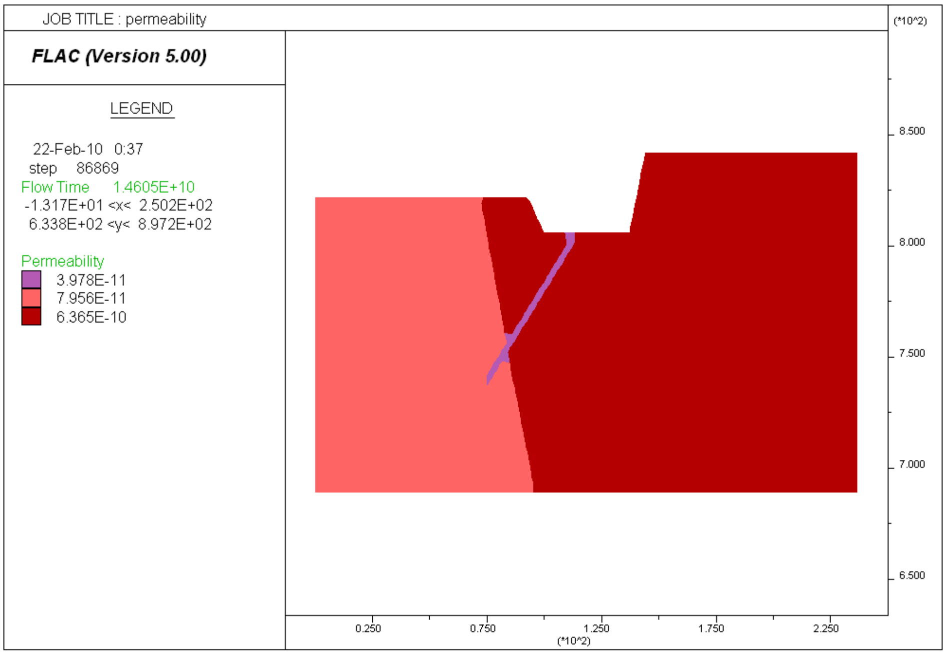


Figure 4. Permeability status at the Asmari and Pabdeh formations and the grout curtain at the dam foundation.

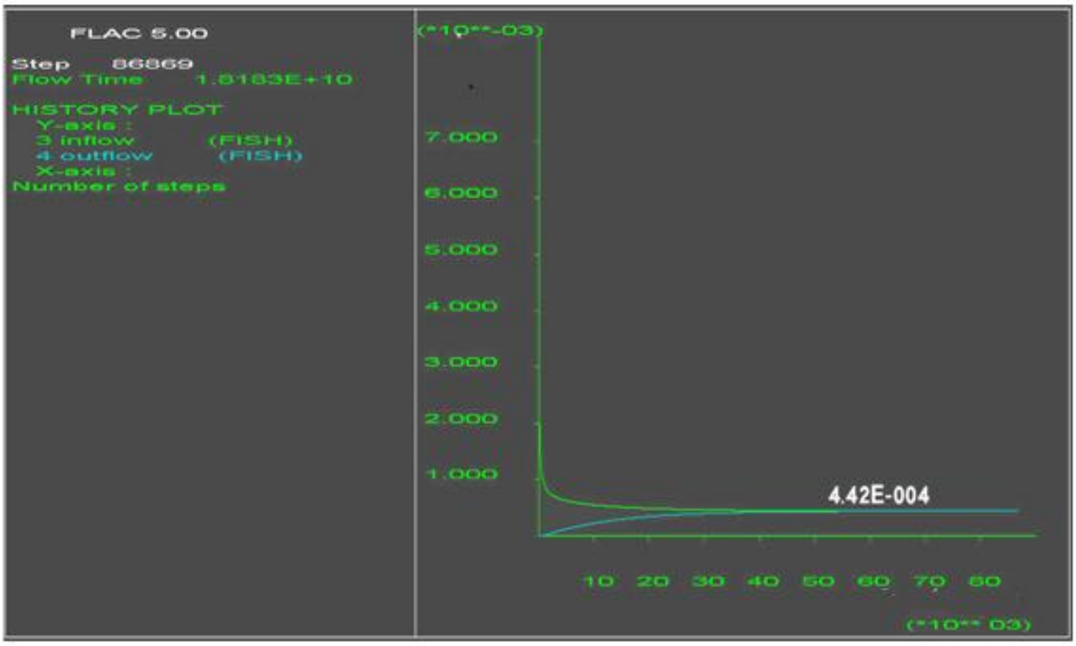


Figure 5. Seepage discharge curve in the dam foundation model in phase one.

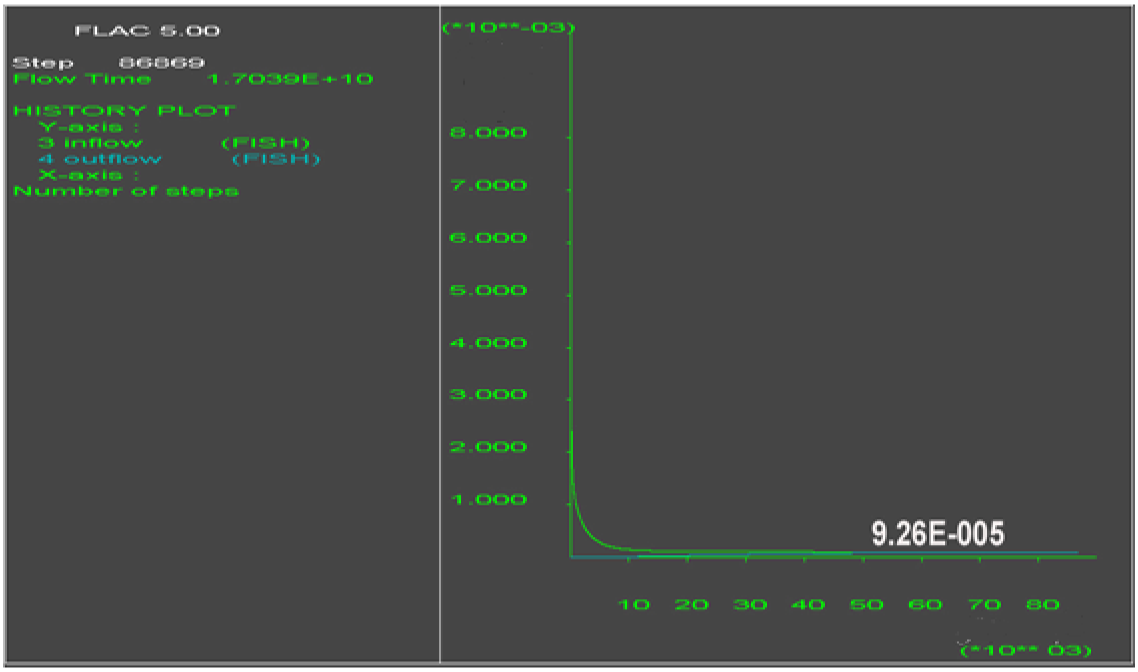


Figure 6. Seepage discharge curve in the dam foundation model in phase four

To analyze seepage in the left abutment, seven different phases were assumed:

1- Phase one: Modeling without a grout curtain
2- Phase two: Modeling with a 46-meter deep grout curtain (length of 53m) below the groundwater level
3- Phase three: Modeling with a 76-meter deep grout curtain (length of 88m) below the groundwater level
4- Phase four: Modeling with a 106-meter deep grout curtain (length of 122m) below the groundwater level
5- Phase five: Modeling with a 141-meter deep grout curtain (length of 163m) below the groundwater level
6- Phase six: Modeling with a 167-meter deep grout curtain (length of 193m) below the groundwater level
7- Phase seven: Modeling with a 184-meter deep grout curtain (length of 213m) below the groundwater level; in this phase the grout curtain is 8 meters deep into the Pabdeh formation.

Since the Asmari foundation has a larger thickness in this abutment, the number of phases is higher than the right abutment. Moreover, from the second phase onward, the curtain length goes 30-35m deeper in each phase (except for the fifth phase) than the previous phase until the curtain penetrates into the Pabdeh formation and the effect of curtain depth on the reduction of seepage becomes evident.

Results of the numerical analysis on this abutment are presented in Table (5).

Table 5. Final results of modeling water flow at the left abutment

Model	Seepage discharge(m^3/s)
Phase one	1.65×10^{-3}
Phase two	1.07×10^{-3}
Phase three	9×10^{-4}
Phase four	7.18×10^{-4}
Phase five (grout curtain of Karun 4 dam)	5.22×10^{-4}
Phase six	3.33×10^{-4}
Phase seven	1.2×10^{-4}

To analyze seepage at the right abutment, the following four phases were assumed.

1- Phase one: modeling without a grout curtain
2- Phase two: modeling with a 46-meter deep curtain (length of 53m) below the groundwater level
3- Phase three: modeling with a 76-meter deep curtain (length of 88m) below the groundwater level
4- Phase four: modeling with a 104-meter deep curtain (length of 120m) below the groundwater level; in this phase, the grout curtain goes 20m deep into the Pabdeh formation.

The curtain length increases to cross the Asmari formation and penetrate into the Pabdeh formation. From the second phase onward, the curtain length increases 30-35m in each stage as compared to the previous stage until the curtain penetrates into the Pabdeh formation and the effect of curtain depth on the reduction of seepage becomes evident. Results of numerical analysis of seepage at the dam foundation are presented in Table (6).

Table 6. Final results of modeling water flow at the right abutment

Model	Seepage discharge(m^3/s)
Phase one	4.89 × 10^{-4}
Phase two	2.51 × 10^{-4}.
Phase three	1.92 × 10^{-4}
Phase four (grout curtain of Karun 4 dam)	9.95 × 10^{-5}

To assess the accuracy of the numerical model, Eq. (3) – developed by Doppit – was used and the discharge of seepage through one section was obtained based on Fig. (7).

$$Q = K \cdot \rho_W \cdot g \cdot \frac{(h_1^2 - h_2^2)}{2L} \qquad (3)$$

Where, Q: Total seepage discharge at the section or model in terms of model thickness ($\frac{m^3}{s}$), K: The equivalent permeability coefficient of the model ($\frac{m^2}{Pa \cdot Sec}$), ρ_W : Water density ($\frac{kg}{m^3}$), g: Gravity acceleration ($\frac{m}{s^2}$), h1: Upstream water level (m), h2: Downstream water level (m) and L: Section or model length (m).

Based on Eq. (3), water seepage discharge at the primary model for the right abutment is obtained as follows.

$$Q = 33.15 \times 10^{-11} \times 10^{-3} \times 10 \times (298^2 - 131^2)/(2 \times 216) = 5.092 \times 10^{-4} m^3/s$$

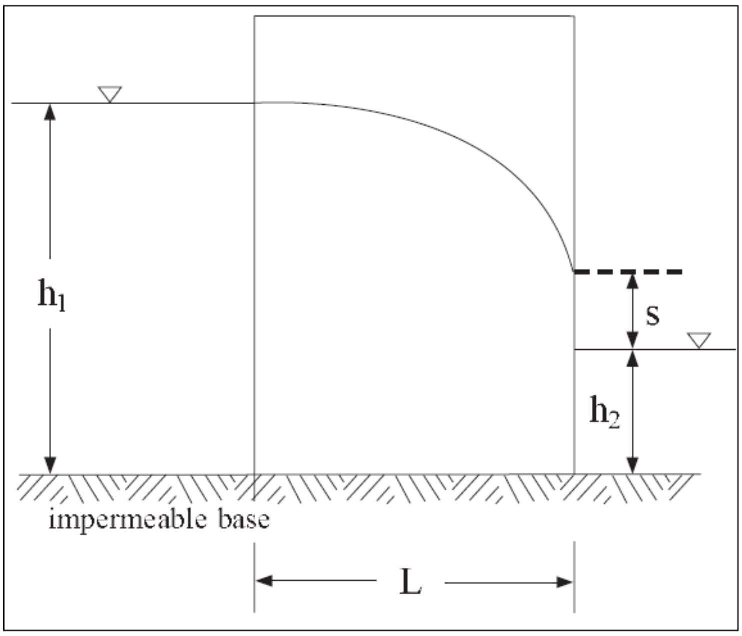


Figure 7. The geometry proposed by Doppit for obtaining seepage discharge at a section [16].

As indicated above, the discharge of seepage obtained using Eq. (4) is almost equal to the seepage discharge obtained through the software analysis.

Due to the advancement of construction techniques, grout curtains can be constructed to high depths and thus grout curtain is one of the most suitable means of sealing the site of Karun 4 dam. In the modeling phase, the effect of grout curtain was studied based on flow efficiency. According to Casagrande, flow efficiency is defined as follows [16].

$$E_q = \frac{Q_\circ - Q}{Q_\circ} \qquad (4)$$

where ,Eq: Grout curtain flow efficiency, Qo: Seepage discharge without grout curtain and Q: Seepage discharge with grout curtain.

Tables 7 to 9 show the flow efficiency of the curtain at the foundation, left, and right abutments.

Table 7. Flow efficiency of the curtain at the dam foundation.

Model	The flow efficiency of the curtain(%)
Phase one	-
Phase two	30.31
Phase three (grout curtain of Karun 4 dam)	47.96
Phase four	79.18

Table 8. Flow efficiency of the curtain at the left abutment.

Model	The flow efficiency of the curtain(%)
Phase one	-
Phase two	35.15
Phase three	45.45
Phase four	56.96
Phase five (grout curtain of Karun 4 dam)	68.48
Phase six	80
Phase seven	92.72

Table 9. Flow efficiency of the curtain at the right abutment.

Model	The flow efficiency of the curtain(%)
Phase one	-
Phase two	48.67
Phase three	60.73
Phase four (grout curtain of Karun 4 dam)	79.75

5. DISCUSSION AND ANALYSIS

The optimal depth of the grout curtain is indicated at the point where an increase in the curtain depth will have no considerable effect on seepage values. Moreover, the effect of injection cost at different depths should also be taken into account. To determine the optimal depth of the grout curtain properly, the following two criteria shall be studied.

1- Grout curtain flow efficiency;

2- Seepage water value and cost of drilling-injection.

The information required for judgments based on the latter criterion is presented in Table (10).

Table 10 Water value and drilling-injection cost [17, 18].

Dam age (year)	Cost per square meter drilling-injection (Tomans)	Value of per cubic meter of water (Tomans)
100	700,000-1,100,000	400-700

According to Table 7, in the fourth phase, the curtain is highly effective where it has penetrated 27 meters deep into the Pabdeh formation. However, in the third phase, the curtain demonstrates a low efficiency, and thus phasethere is no need to consider the second criterion in choosing between the two options in this phase. Therefore, the optimal depth in this stage is selected only based on the flow efficiency of the curtain in the fourth phase, i.e. the phase in which the curtain goes 27 meters deep into the Pabdeh formation.

According to the results as illustrated in Table 8, since the permeability coefficient of the left abutment in the Asmari formation is higher than that of the right abutment, the grout curtain depth should continue to a point where a low seepage discharge is obtained. Therefore, the grout curtain shows satisfactory flow efficiency in the fifth, sixth, and seventh phases according to the results obtained for this abutment phase. Results of calculations in these phases are presented in Tables 11 and 12.

By comparing these tables, it is concluded that in the seventh phase, the grout curtain is highly efficient while the value of the seepage water is also higher. Therefore, phase seven is selected as the phase with the optimal grout curtain depth.

According to Table 9, at the right abutment, the curtain demonstrates high efficiency in the fourth phase where it is 20 meters deep into the Pabdeh formation. In this phase, the discharge of seepage through abutment is low. However, it shall be noted that in the third phase, the seepage discharge is also low and the curtain is satisfactorily efficient. Therefore, the second criterion is used for choosing between these two options. The difference between drilling depths in the third and fourth phases is 32 meters. By assuming a thickness of 3 meters for the grout curtain and a maximum drilling-injection cost of 1,100,000 per square meter the total drilling-injection cost for this difference is as follows:

$$32 \times 3 \times 1,100,000 = 105,600,000$$

By assuming a lifetime of 100 years for the dam and an average water value of 500 Tomans/m^3, the value of the seepage water is:

$$(1/92\times10^{-4}-9/95\times10^{-5})\times100\times365\times$$
$$24\times3600\times500\cong145854000$$

It is observed that the value of seeped water is much higher than the drilling-injection cost. Therefore, the fourth phase depth, where the grout curtain is 20 meters deep into the Pabdeh formation, is selected as the optimal depth for grout curtain. It is worth mentioning that in the drilling-injection calculations, the maximum price is taken into account. The grout curtain shall be built in a way that it crosses the layer with higher permeability. It also should be sewed to a layer with lower permeability unless the value of seepage water is lower than drilling-injection costs. Otherwise, the curtain will not show the target efficiency. Consequently, as shown in Table (8), in the fifth phase where the depth recommended by the consulting company is used, the efficiency of the curtain proves to be as low as about 68.48%. With an increase in the curtain depth, when the curtain is sewed to the Pabdeh formation, the efficiency increases to 92.72%. Table (6) shows the same growth. As the result, from the third phase (recommended by the consulting company) to the fourth phase, efficiency increases from 47.96% to 79.18%. Hence in the first place, the main measure for studying the grout curtain is sewing the curtain to a layer with lower permeability. Studies revealed that increasing the curtain depth after sewing it to a layer with lower permeability does not have a significant effect on the flow efficiency of the curtain. Then, considering the value of seeped water, the drilling-injection costs, and variations of pore water pressure, this depth could be finalized. It should be noted that to ensure the stability of the dam, the pore water pressure has to be lower than normal stress.

Studies on pore water pressure and flow lines also reflect the high efficiency of the grout curtain in a phase in which the curtain is sewed to the Pabdeh formation. In this phase, as seen in Figs. 8 and 9, at the right abutment, the construction of the grout curtain reduces pore water pressure at the model downstream, while no change in pore water pressure is observed at the upstream. The results of these changes are presented in Table 13.

Table 11. The comparison between phases five and six at the left abutment.

Difference in drilling-injection depths (m)	Drilling-injection costs (Tomans)	Seeped water value (Tomans)
30	99,000,000	298,000,000

Table 12. The comparison between phases six and seven at the left abutment.

Difference in drilling-injection depths (m)	Drilling-injection costs (Tomans)	Seeped water value (Tomans)
20	66,000,000	336,000,000

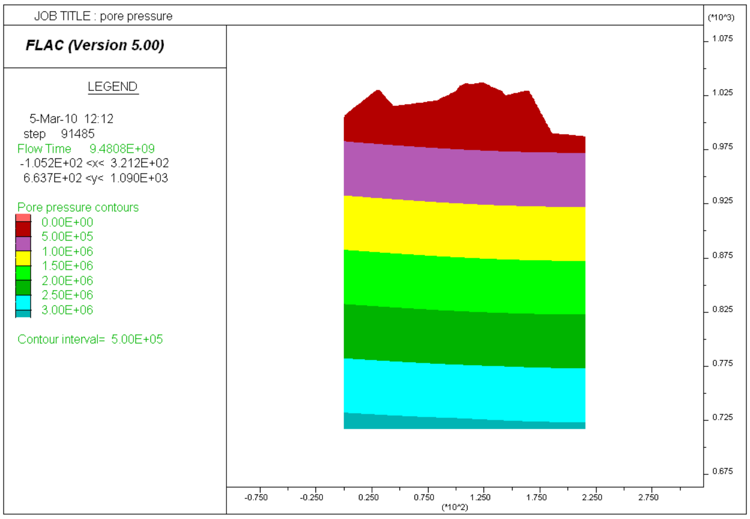


Figure 8. Distribution of pore water pressure at the right abutment without a grout curtain.

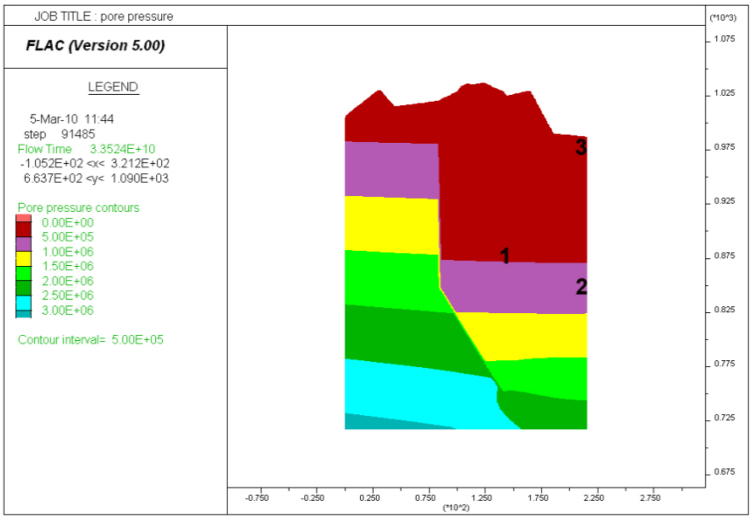


Figure 9. Distribution of pore water pressure at the right abutment when the curtain is sewed to Pabdeh formation.

Table 13. Pore pressure at three points of the model in the right abutment.

Points	Coordinates	Pore pressure without grout curtain (Pa)	Pore pressure in the final phase (Pa)
Point 1	(143, 867)	1.46×10^6	4.44×10^5
Point 2	(214, 851)	1.71×10^6	6.99×10^5
Point 3	(214, 986)	3.4×10^5	0

The effect of the curtain on changes in flow lines can clearly be seen in Figs. 10 and 11. The results of the modeling at the left abutment and dam foundation also show that the construction of grout curtain lacking optimal depth changes flow line paths.

Construction of the curtain reduces pore pressure at the model downstream. Moreover, after constructing the curtain, pore pressure at the upstream remains unchanged. The results of the changes are presented in Tables 14 and 15. The front grout curtain blocks water seepage to a great extent and prevents the flow of water from the model upstream to the downstream. As a result of the reduction in the water flowing to the downstream, water pressure at the downstream declined after the grout curtain had been built.

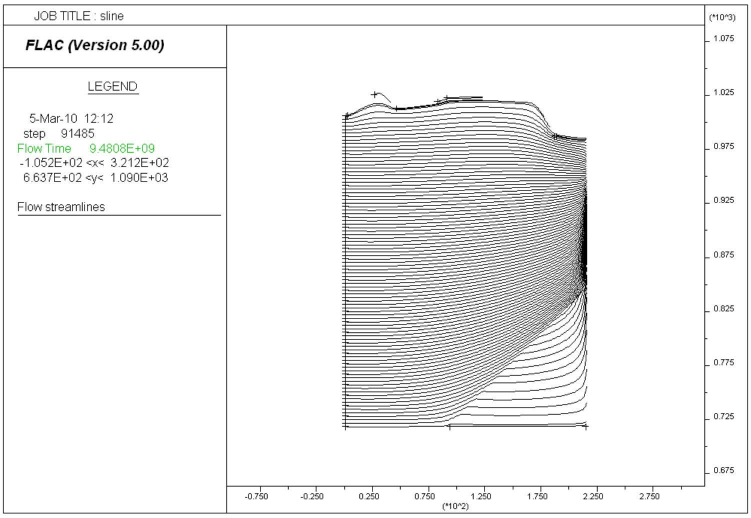


Figure 10. Flow lines at the right abutment without a grout curtain.

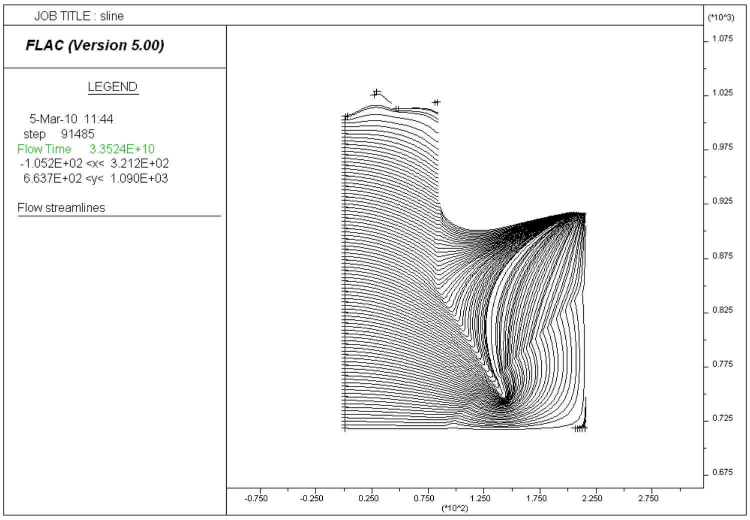


Figure 11. Flow lines at the right abutment when the curtain is sewed to the Pabdeh formation.

Table 14. Pore pressure at three points of the model at the left abutment.

Points	Coordinates	Pore pressure without grout curtain (Pa)	Pore pressure in the final phase (Pa)
Point 1	(52, 842)	1.71×10^6	2.94×10^5
Point 2	(1, 849)	1.61×10^6	2.14×10^5
Point 3	(1, 957)	5.22×10^5	0

Table 15. Pore pressure at two points in the dam foundation.

Points	Coordinates	Pore pressure without grout curtain (Pa)	Pore pressure in the final phase (Pa)
Point 1	(233, 838)	1.18×10^5	1.02×10^5
Point 2	(122, 779)	1.43×10^6	8.20×10^5

6. CONCLUSIONS

Analyses revealed the following points:

1- At the dam foundation, seepage discharge after the construction of a grout curtain featuring optimal depth (i.e. phase four) decreased by 4.394×10^{-4} m^3/sec. That is to say, when the curtain is sewed to the Pabdeh formation, it demonstrates an efficiency of 79.18%.

2- At the left abutment, seepage discharge following the construction of a grout curtain with the optimal depth (i.e. phase seven), where the curtain is sewed to Pabdeh formation, is reduced by 1.53×10^{-3} m^3/sec and curtain efficiency is 92.72%.

3- At the right abutment, seepage discharge following the construction of a grout curtain featuring optimal depth (i.e. phase four), where the curtain is sewed to the Pabdeh formation, is reduced by 3.895×10^{-4} m^3/sec and curtain efficiency is 79.75%.

4- The results suggest that the optimal depth of the grout curtain at the abutments and foundation is obtained by sewing the curtain to the Pabdeh formation.

5- In calculating the drilling-injection costs, the maximum drilling-injection cost per square meter was taken into account, and for determining the value of seeped water, the average water value per cubic meter was used. Using "drilling-injection costs calculation coefficient" and the calculated seeped water for a lifetime of 100 years, it was proved that the optimal depth of grout curtain at the abutments and foundation was completely cost-effective compared to the seepage water value. Therefore, this depth can meet drilling-injection costs for an increase in curtain depth.

6- The construction of a grout curtain leads to a reduction in pore pressure at the downstream, while no change is observed in the upstream pore pressure. Moreover, construction of the curtain changes the flow line paths.

REFERENCES

[1] Bouwer, H., GroundwaterHydrology. (Translator: LotfiSedigh, A.), publishing Sahand University of Technology, 1994.

[2] Alkaya, D., and YeŞdl, B., Grouting applications of grout curtains in Cindere dam and hydroelectric power plant. Scientific Research and Essays, 2011. **6**(19): p. 4039-4047.

[3] Aalianvari, A., Katibeh, H., Sharifzadeh, M., A new approach for computing permeability of fault zones case study: the upper reservoir of Azad pumped-storage power station in Iran. ArchMin Sci, 2010. **55**(3): p. 605–621.

[4] Baghbanan, A., Jing, L., Hydraulic properties of fractured rockmasses with correlated fracture length and aperture. Int J RockMech Min Sci, 2007. **44**(5): p. 704–719.

[5] Weaver, K., and Bruce, D.A., Dam Foundation Grouting, Revised and ExpandedEdition. American Society of Civil Engineers, ASCE Press, New York, 504 p., 2007.

[6] Wilson, D., and Dreese, D., Grouting Technologies for Dam Foundations. Proceedings of the Annual Conference, ASDSO, Las Vegas, Nevada, 1998.

[7] Nonveiller, E., Injection engineering operations. publishing Zayandab consulting engineers Co., 1995.

[8] Najjar, Y.M., Naouss, W.A., Seepage design charts for flat bottom dams on heterogeneous media. Int.J.for Numerical and Analytical Methods in Geomechanics, 1995. **19**: p. 637-651.

[9] Ewert, F. K., Permeability, Groutability and Grouting of Rocks. related to dam sites. Dam engineering, 1997. **VIII**(1): p. 31-76.

[10] Sivakan, N., Permeability and Seepage, Chapter 7, http://www.geoengineer.org/files/siva-seepage.pdf. 2005.

[11] Aalianvari, A., Optimum depth of grout curtain around pumped storage power cavern based on geological conditions. Bull EngGeol Environ, 2014. **73**(3): p. 775–780.

[12] MahabGhodss consulting engineering Co., Technical report of Karun 4 dam and power plant. 1997.

[13] MahabGhodss consulting engineering Co., Rock mechanics report of Karun 4 dam and power plant. 2002.

[14] MahabGhodss consulting engineering Co., Engineering geology report of Karun 4 dam and power plant. 1996.

[15] Itasca Consulting Group, Flac 2 D, Fast Lagrangian Analysis of Continua, User's Manual Version 5. 2004.

[16] EM 1110-2-1901, Seepage control in Earth Foundations, chapter 9. USBR Reports, 1986.

[17]Website:http://www.magiran.com/npview.asp?ID =1877070.

[18]Website:http://www.amirparizad.com/index.php?option=com_content&task=view&id= 3252&Itemid=36.