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Research Article

NUMERICAL ANALYSIS OF SEEPAGE THROUGH EMBANKMENT DAMS (CASE STUDY: KOCHARY DAM, GOLPAYEGAN)

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ABSTRACT
Study of seepage through foundation and dam body is one of the important factors in design and construction of embankment dams in order to ensure sustainability and control water loss. In the present study, the amount of seepage through Kochary Embankment Dam is studied. The study area is geographically located in Golpayegan city of Isfahan province. The dam site is located in tectonic-sedimentary domain. The dam bedrock is composed of sandstone, and its scour-colluvial foundation is composed of silty sand, sandy silt and gravel. Analyses show that the rock foundation has a very low permeability coefficient and scour-colluvial deposits of both abutments have a moderate to high permeability. Seep/w software is used for numerical analysis of seepage that uses finite element method to seepage numerical analysis. The annual seepage in the foundation is equal to 750,000 cubic meters per year which is economically equivalent to 34.7% of the volume of the reservoir which is not acceptable. So, for sealing dam foundation, sealing trench method and sealing wall method have been used. After sealing foundation by sealing trenches, water seepage in foundation will reduce to 41,300 cubic meters per year which is equivalent to 1.91% of the volume of the reservoir which is acceptable. Scour issue is technically an important issue which has been solved after the construction of water trenches and seepage was eventually reduced to 1.63% of the reservoir volume.

***Keywords**: Permeability Coefficient, Seepage, Sealing, Scour, Seep / w Software*

INTRODUCTION
Water is one of the most urgent and critical human needs that especially with the increasing population and the need for agricultural and industrial development on the one hand and limited water resources on the other hand, becomes increasingly sensitive. Water scarcity and the gradual unfolding of its true and critical value caused that people and countries try to utilize the available water as much as possible. Among the man-made structures, dams, for various reasons, including the importance of the construction purposes and the intensity and sensitivity of the risks and damage caused by possible failure, have a unique position. In Iran special attention has been paid to dam construction. However, because of the geographical location of our country in a region of the planet, that has rainfall less than the world average and because in most parts of Iran we have only seasonal rainfalls, surface water collection and control is especially important. Especially in the last two decades, considerable attention has been paid to surface water control and construction of embankment dams (Alvarez *et al.*, 1982).
Water molecules flow in the soil porous media due to their potential energy and gradually lose their energy because of friction in this environment. This phenomenon is called water seepage in the soil porous environment which has undesirable effects as follows:

- Loss of water stored behind the dam structure
- Generation of pore pressure in porous media and reduction of effective stress between soil particles and thus reduction of its shear strength
- Applying uplift pressure to impermeable structures (such as concrete structures, steel structures, etc.)
- Movement of soil particles and occurrence of internal erosion in the environment
- Imposition of seepage force on soil in the direction of flow

Each of the above issues can have a negative effect on the sustainability of embankment dams, hence the sustainability analysis should be considered. To reduce the negative effects of seepage phenomenon in the soil environment, using suitable methods it is necessary to reduce the potential energy of water molecules and thereby the amount of seepage as much as possible. Since it is practically impossible to reduce the amount of seepage in the soil to zero, some methods should be used to control and prevent particles movement in the environment (Evert, 1985).

Despite the studies carried out before construction of a dam, the hydraulic behavior of dam body or its adjacent geological formations cannot always be accurately predicted, so the probability of seepage or penetration after construction of the dam is almost certain. The severity of seepage or penetration in many cases is acceptable until the safety of dam has not been at risk. Many dams' collapses or at least some of them have been occurred because of inadequate detailed information about the hydraulic properties of existing vessels in the geological formation at the dam site. Many reservoirs of dams built in the world have seepage (Rooh-Allah, 2008), this seepage may occur through the geological formation at the dam site or the dam body. However, seepage is inevitable for various reasons, such as non-uniform subsidence or earthquake, etc. during the operation of the reservoir, but properly constructed dams are less affected by the seepage. Nonvieller (1988) stated that seepage through foundation (increase of groundwater flow through the foundation) leads to the following consequences:

- Increased uplift pressure on the foundation that may cause damage or instability in the structure.
- Drainage flow in fractures and holes in foundation materials can cause erosion, increase rock natural permeability or cause hydraulic failure in granular soils (Rahmani, 2009).
- The reservoir water loss can scratch the reservoir duty of water storage and make it economically unjustified (Nonvieller, 1989).

Experiments have shown that seepage through the reservoir will lead to significant economic repercussions and rehabilitation efforts are usually expensive, so in this case, the research that has been done before can be very beneficial, that increases the importance of this issue and makes clear the need for such research (Hussainpour, 2009).

Water supply is essential in Kochary village in Golpayegan city of Isfahan province which has suitable climatic conditions for the development of garden and agricultural land. Regardless of the type of dam built in an area, studies and investigations are necessary which are changed depending on the conditions of the area, dewatering situation, the basin extent, etc. Among these discussions, engineering geology is significantly important. Due to the large volume of water stored in the reservoir, geological conditions vary in dam area and these changes are caused by high hydrostatic pressures applied to dam foundation and abutments. So the suitable design of a dam requires a variety of studies in different fields, including a detailed study on engineering geology and hydrogeology conditions of dam site. In the field of engineering geology selection of the dam site, selection of the dam type and design of dam sealing wall are used. On the other hand, the amount of seepage and water loss through the dam foundation and body as well as calculation and determination of its value and also methods to prevent and reduce the amount of seepage and water loss are particularly important. In the present study, we tried to estimate the amount of water seepage through the foundation and body of Kochary Embankment Dam located in Golpayegan city of Isfahan province using results of different tests related to the phenomenon of seepage and related calculations and existing software and present the best solution to prevent or reduce the seepage (Iranian National Committee on Large Dams, 1996).

Geographical Location and Characteristics of Kochary Dam

Kochary Dam is located in Golpayegan city of Isfahan province. The access road to the site is the asphalt road which begins from Golpayegan and continues to Aligudarz. In the 5-kilometer of the mentioned road there is a diversion road which continues to the dam site.

This road, which has a length of about 3 km, ends to the left abutment of the dam in the downstream and access to other parts of the site is possible through local access roads. The location of the project is shown in Figure 1.

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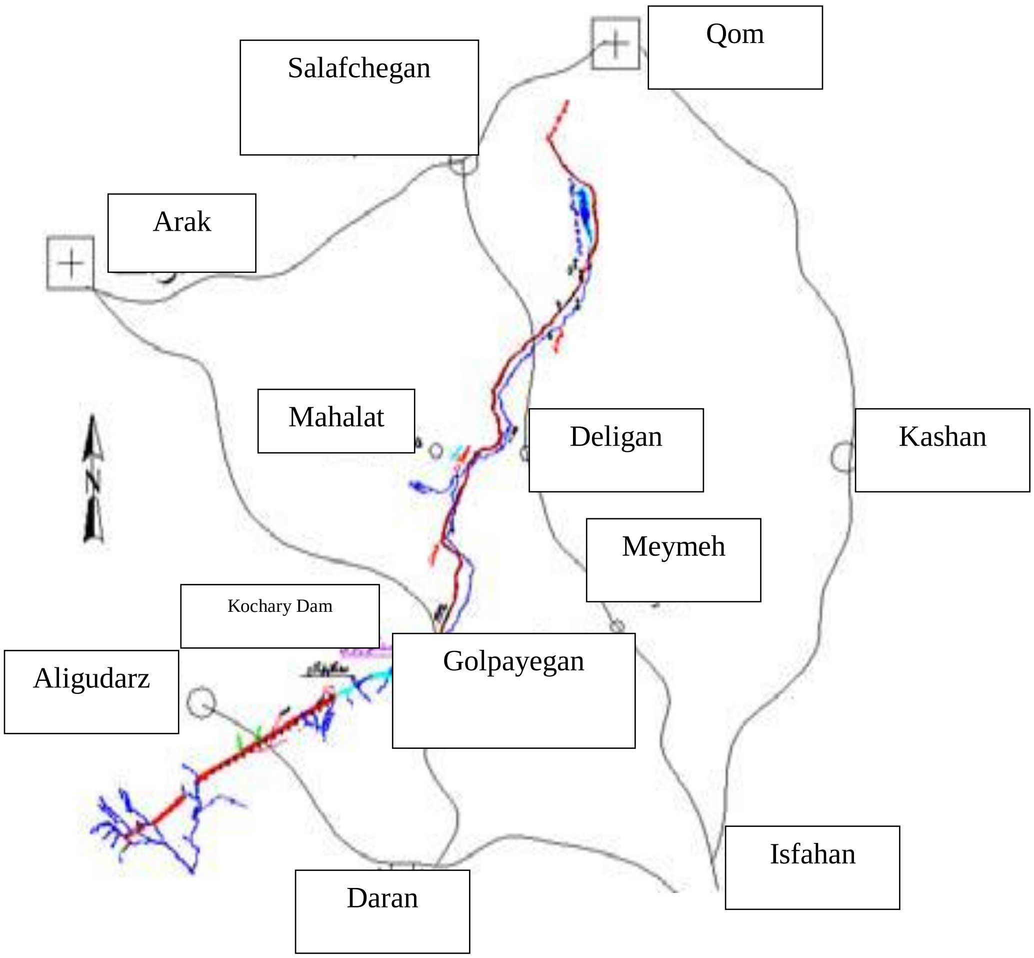

Figure 1: The Location of Kochary Embankment Dam

Characteristics of Kochary embankment dam can be summarized as follows:

- The dam height from the base of the river: 33 m
- The dam crest length: 150m
- The dam crest level: 1205
- The dam free board: 3 m
- Normal level of water in the reservoir (overflow level): 1202 m
- Reservoir level in normal level: 207,959 m^2
- Balancing volume of the dam: 2967252 m^3
- The minimum operating level (intake level): 1181 m

MATERIALS AND METHODS

Methodology

Situation of Kochary Site

The Kochary site has a foundation composed of soil and rocks where alluviums have covered the bedrock. The thickness of alluvial deposits is different in left and right side of dam axis so that the thickness of the alluvial deposits in left and right side is equal to 17 and 8 m on average, respectively. Stratigraphic section of the dam axis is shown in Figure 2.

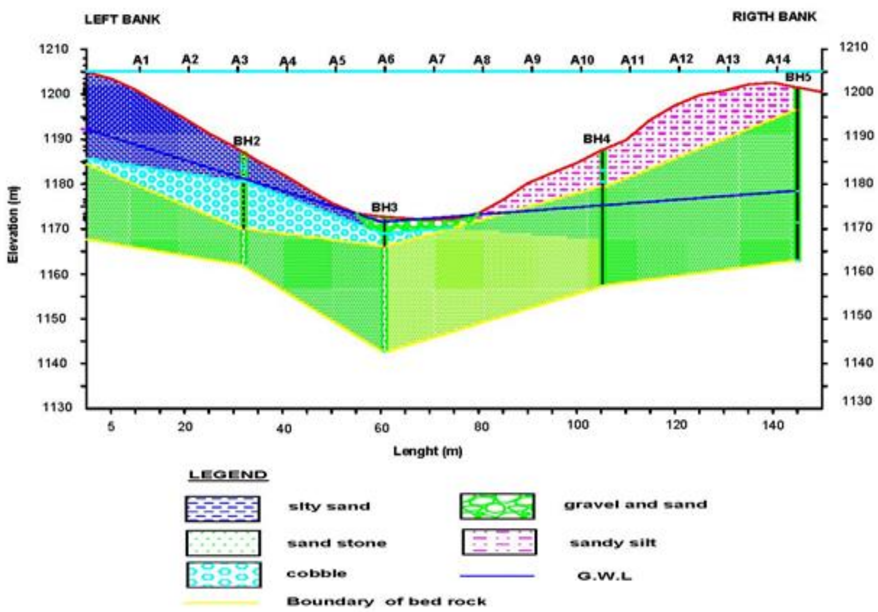

Figure 2: Stratigraphic Section of the Kochary Dam Foundation

As shown in Figure 2, the rock part of the foundation is composed of sandstone and in the river bed alluvium is composed of coarse-grained gravels, the left side is composed of silty sand and the right side is composed of sandy silt.

To provide the permeability section, at first the position of exploration boreholes drilled by machines (rotary) has been implemented on the dam axis section and by inserting the permeability coefficient values in the sections tested by each borehole, a permeability column was defined. It has been tried to identify the distance between boreholes and determine permeability zones using the interpolation method. The permeability section of the foundation is given in Figure 3.

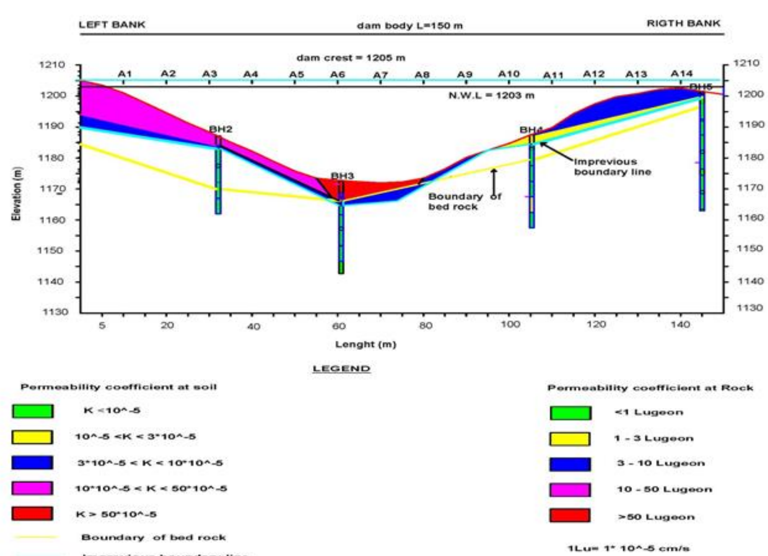

Figure 3: The Permeability Section of the Kochary Dam Foundation

Scour-Colluvial Foundation

The alluvial foundation in the dam axis is divided into two permeable and impermeable parts and here the basis of separating the permeable part from the impermeable part is the permeability coefficient. So that the index of impermeable boundary is equal to $1*10^{-5}$ cm/s. The thickness of impermeable part in the left side is greater than its thickness in the right part. In general, the thickness of the alluvial materials in the left part is greater than the right part. The alluvial foundation of the dam axis has different permeability in different parts.

The permeability coefficient for materials in alluvial permeable part varies between $2.5*10^{-5}$ cm/s and $4.9*10^{-2}$ cm/s.

According to the distribution of different permeability zones in the different parts of the foundation and also their different coverage level percentage, the average equivalent permeability coefficient is equal to $7.23*10^{-2}$ cm/s.

The thickness of alluvial deposits in the river bed below the dam body in upstream and downstream is considered equally due to lack of adequate information.

Rock Foundation

The Kochary Dam bedrock is composed of sandstone which according to Logan tests that have been conducted in various boreholes the rock foundation has a low permeability coefficient. Here the impermeable boundary index in rock is considered as 3 Logan.

The depth of bedrock in the left part is between 6.5 and 20.5 m and in the right part this depth is between 6.5 and 11.5 on average. In all sections except sections A6 and A7 and A8 the rock part is impermeable and sealing is not required so the bedrocks of left and right parts are impermeable and only the river bed is permeable.

The maximum depth of the rock foundation is observed in the whole BH1 and the minimum depth is observed in the borehole BH3. Logan values for all tested sections were less than 1, the permeable boundary index at the dam axis was equal to 3 Logan and $1*10^{-5}$ m/s based on the rock permeability.

Seepage Through the Foundation

Three following assumptions have been considered to calculate seepage through the foundation of Kochary Embankment Dam:

The first assumption:

To calculate the seepage, the impermeable boundary under the foundation has permeability coefficient less than $1*10^{-5}$ m/s in alluviums and less than 3 Logan in rocks.

The second assumption:

This assumption is related to the use of finite element method for numerical analysis of seepage in rock part. Considering that all analyses performed in rock mass, including stress-strain, rupture, seepage, etc. in modeling are done based on numerical analysis using finite element method, in this section, due to the thin stone layer as well as the lack of two analytical methods in a software, the seepage in the rock was investigated using the finite element method considering a conventional safety factor.

The third assumption:

1 Logan=10^{-5} is assumed as equivalent permeability coefficient between the soil and rock, based on Barton and Kovadrous (2003).

Before calculating the seepage, first by plotting permeability sections of the dam foundation, in 14 sections (the number of these sections based on geological properties in the area and also change in the properties of soil and rock can be increased and decreased, obviously by increasing the number of sections more accurate seepage analysis can be done) based on the thickness of the layers of soil and rock, and the thickness of each layer, equivalent permeability was calculated and the results can be seen Table 1.

To calculate the amount of water seepage through the foundation at each section Table 1 was set to determine the geometry of the body and foundation, according to the location of the dam.

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Table 1: Geometry of the Body and Foundation of Kochary Embankment Dam

Section	The Horizontal Distance the Upstream Crust (m)	The Horizontal Distance the Downstream Crust (m)	The Base of the Core(m)
A1	12	10	7.4
A2	24	25	11.4
A3	39	65	19.8
A4	57	77.5	24.2
A5	87	85	29.4
A6	93	92.5	31.4
A7	90	90	30.6
A8	81	92.5	29.8
A9	69	92.5	28.2
A10	57	52.5	20.2
A11	51	35	16.6
A12	48	17.5	13.4
A13	30	10	9.8
A14	24	5	8.2

After determining the geometry of the body and foundation, it was modeled in Seep / w.

Characteristics of Seep / w Software

- Numerical analysis in this program is done based on finite element method.
- The software is modeled hydraulic conductivity and soil moisture as a function of pore water pressure as continuous functions, while other software applications use unrealistic assumptions and model this parameter as stepped that leads to an error in calculation.
- The range of this analysis, in addition to saturated soils also includes unsaturated soils. This matter is the important difference between this software and other soil engineering softwares.

Using the boundary conditions, we can reach the final solution of the problem that these conditions were applied as follows:

All conditions have been applied on the nodes so that the nodes located in the reservoir levels have fixed total load equal to the normal height of the reservoir and total load of nodes located in downstream heel levels was considered equal to gravity load of each node (node height above the sea level). In the lateral abutments and impermeable bed of the foundation, due to the lake of flow exchange, the flow rate is considered as zero.

- To determine the boundary conditions and solve equations, h node values are obtained. By calculating h in nodes, equipotential lines and the flow can be outlined, that are shown in following figures.

RESULTS AND DISCUSSION

Sections Models

All fourteen sections have been modeled in See/w software and seepages from bed to impermeable boundary have been studied which are shown in Figure 4. Figures of seepage in each section show equipotential lines, flow lines, flow network, the geometry of the studied area, elements of the dam body and eventually seepage rate per unit width.

Figure 4 shows four studied cross sections.

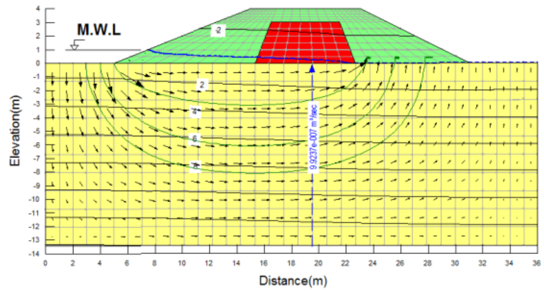


Figure 4: a) Section 1

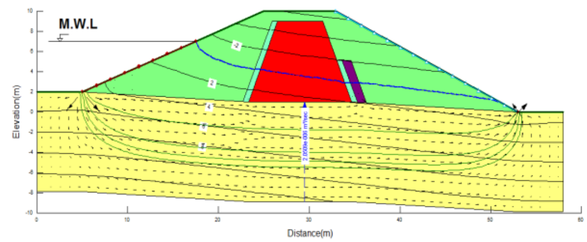


Figure 4: b) Section 2

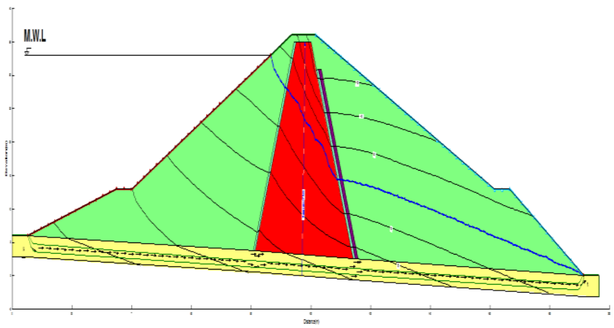


Figure 4: c) Section 3

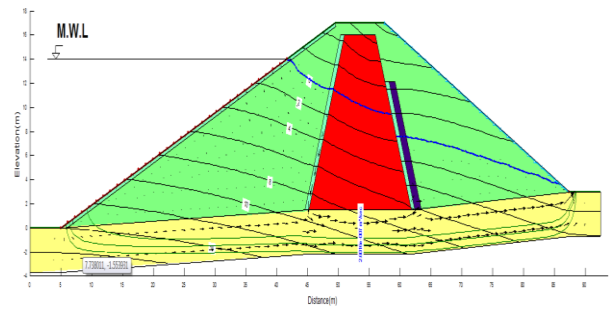


Figure 4: d) Section 4

Figure 4: Seepage models of Kochary Embankment Dam using seep / w software (in above figures, the blue line indicates the water flow, the arrows indicate the direction of flow, the green lines indicate flow lines and the black lines indicate equipotential line in Kochary Embankment Dam foundation. Number of each section is specified below each figure).

After plotting and calculating seepage from all sections, to calculate the annual seepage through the dam foundation, first the seepage speed of each section was calculated in meters per year and then by calculating the area between sections, water seepages between the sections were calculated separately and calculations are summarized in Table 2.

Sealing the Foundation

One way to deal with the phenomenon of particles leaching from the core to the foundation which occurs due to the intense pressure difference between the two sealed sides and also the downstream of the core and the seal part, is to reduce the degree of sealing of the sealing wall.

However, this creates another problem, which is high permeability of the foundation and a significant increase in the amount of seepage. Experience has shown that according to above limitations, the best situation for the sealed part in terms of infiltration, is the situation between two above limits, i.e. the permeability of the sealed part should not be too low which creates pressure difference between two sealed sides, and should not be too high which increases water seepage.

Based on experience, the best degree of sealing for the sealed part is about 65 percent, because in this case it is easier to spread the pore pressure and the amount of losses caused by seepage can be ignored (Rahimi, 2010). Here it is used as a sealing design.

Table 2: The Amount of Seepage Through the Kochary Embankment Dam Using Seep / w

Section No.	**Seepage Speed**	**Seepage Speed**	**The Area Between two Sections**	**The Seepage Between two Sections**
	(m/s)	(m/year)	(m^2)	(m^3/year)
1	4.14E-07	1.31E+01	141.6	9.24E+02
2	2.05E-06	6.46E+01	112.4	8.65E+03
3	2.83E-06	8.92E+01	69.02	4.70E+03
4	1.49E-06	4.70E+01	39.9	1.68E+04
5	2.52E-05	7.95E+02	41.34	1.21E+05
6	1.60E-04	5.05E+03	55.2	3.78E+05
7	2.74E-04	8.64E+03	50.36	2.19E+05
8	1.69E-06	5.33E+01	21.57	7.29E+02
9	4.53E-07	1.43E+01	18.06	1.60E+02
10	1.10E-07	3.47E+00	6.86	3.96E+01
11	2.56E-07	8.07E+00	27.7	2.38E+02
12	2.88E-07	9.08E+00	59.8	3.36E+02
13	6.87E-08	2.17E+00	76.8	8.32E+01
14	6.01E-22	1.90E-14	64.6	6.12E-13
15	0.00E+00	0.00E+00	16.67	0.00E+00
Total seepage through the alluvial foundation				7.50E+05

Many dams in the world are constructed with the main objective of water supply or power generation and flood control is considered as a secondary objective. Thus, the economic aspect is very important in the water supply. Water seepage is considered as an effective factor in economic feasibility of storage dam projects.

So an amount of water entering the reservoir is defined as the seepage cutoff. This cutoff in engineering can be determined by Logan number or water entry rate at a given pressure for the rock and soil parts by calculating the boiling.

This value is the optimum value that is determined based on the interaction of two factors including the cost caused by water loss and the cost of sealing the environment.

Earlier seepage through the dam foundation at each section and ultimately entire foundation is measured using Seep / w software which is equal to 750,000 cubic meters per year.

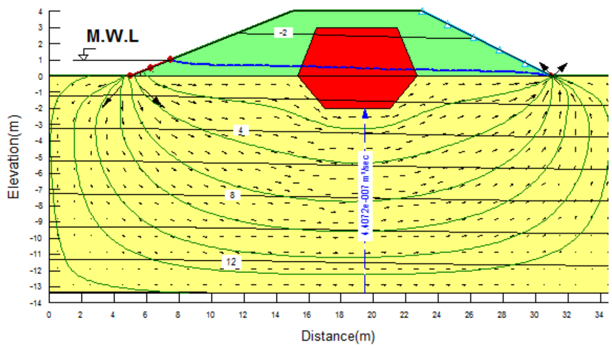
With regard to the economic value of any project in which maintenance and storage is important, the allowed seepage per a year, is considered as on average, about 5% -2% of the total volume of the reservoir that in the Kochary Embankment Dam project, the ratio of water seepage volume to the reservoir volume is equal to 34.7%, which indicate that in the water seepage in this project is economically a problem.

So to achieve the allowable seepage, the dam needs to be sealed, and due to the project characteristics and alluvial foundation, sealing trenches are used for sealing. The thickness of the permeable part and depth and slope of the sealing trench as well as the thickness of permeable part after trenching are shown in Table 3.

Table 3: Permeable Layer Thickness and Depth of the Sealing Trench in Kochary Embankment Dam

Section	The Initial Thickness of the Permeable Part (m)	The Thickness of the Permeable Part Sealing (m)	The Residual Depth after Sealing (m)	Trench Slope (m)	Trench Depth (m)	Thickness of Permeable Part after the Construction of Trenches (m)
A1	13.35	8.7	4.7	1/1	2	11.35
A2	9.88	6.4	3.5	1/1	2	7.88
A3	5.04	3.3	1.8	1/1	4	1.04
A4	4.87	3.2	1.7	1/1	3	1.87
A5	4.29	2.8	1.5	1/1	3	1.29
A6	6.5	4.2	2.3	1/1	6.5	0
A7	3.1	2.0	1.1	1/1	3.1	0
A8	1.6	1.0	0.6	1/1	1.6	0
A9	1.5	1.0	0.5	1/1	1.5	0
A10	1.2	0.8	0.4	1/1	1.2	0
A11	3.7	2.4	1.3	1/1	1	2.7
A12	7.6	4.9	2.7	1/1	1	6.6
A13	7.1	4.6	2.5	1/1	1	6.1
A14	5.1	3.3	1.8	1/1	1	4.1

Then, sealing trenches are plotted under the dam foundation using Seep / w and images and figures observed in Figure 5 are obtained. Four plotted sections are shown in Figure 5.



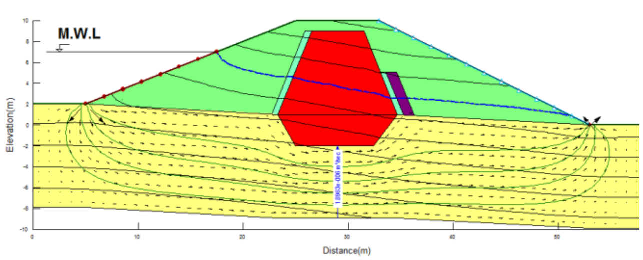


Figure 5: a) Section 1

Figure 5: b) Section 2

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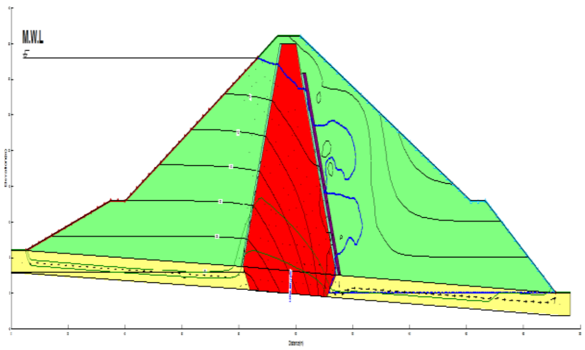

Figure 5: c) Section 7

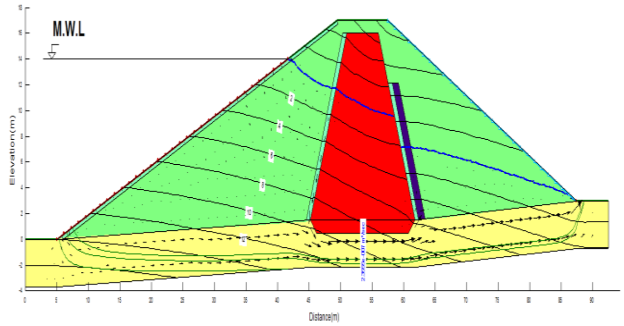

Figure 5: d) Section 11

Figure 5: Models of the dam sections after construction of sealing trench in Seep / w (in above figures, the blue line indicates the water flow, the arrows indicating the direction of flow, the green lines indicate flow lines and the black lines indicate equipotential lines in the Kochary Embankment Dam. Number of sections is shown below each figure.)

Using the above figures and values obtained from them, the seepage through the dam foundation after the construction of the sealing trench is obtained, which is shown in Table 4.

Table 4: The Amount of Seepage Through the Kochary Embankment Dam After the Construction of Sealing Trench

Section No.	Seepage Speed	Seepage Speed	The Area Between Two Sections	The Seepage Between Two Sections
	(m/s)	(m/year)	(m^2)	(m^3/year)
1	4.40E-07	1.39E+01	122.5	8.50E+02
2	1.89E-06	5.96E+01	96.4	5.96E+03
3	2.03E-06	6.40E+01	49.8	3.30E+03
4	2.17E-06	6.84E+01	14.6	9.32E+03
5	3.83E-05	1.21E+03	15.7	1.54E+04
6	2.41E-05	7.60E+02	11.43	6.05E+03
7	9.45E-06	2.98E+02	0	0.00E+00
8	0	0.00E+00	0	0.00E+00
9	0	0.00E+00	0	0.00E+00
10	1.24E-09	3.91E-02	0	0.00E+00
11	2.33E-07	7.35E+00	15.5	1.08E+02
12	2.07E-07	6.53E+00	46.5	2.18E+02
13	9.03E-08	2.85E+00	63.4	9.03E+01
14	1.51E-21	4.76E-14	51	1.21E-12
15	0.00E+00	0.00E+00	14.39	0.00E+00
Total seepage through the alluvial foundation				4.13E+04

After the construction of sealing trench, the permeable area is reduced as 300 m^2 to 502 m^2 and therefore, the amount of average seepage per square meter reaches to 82.27 m^3 per year. According to the Table 4, seepage through the dam foundation reaches to 41300 m^3 per year, and the ratio of the seepage volume to the reservoir volume will be equal to 1.91 percent. So given that the allowable seepage through the dam foundation, is on average considered as about 5% -2% of the total reservoir volume per year, by constructing sealing trench the seepage through the Kochary Embankment Dam foundation will reach to 1.63% which is an allowable value.

Conclusion

In the present study, the amount of water seepage through Kochary Embankment Dam of Golpayegan was studied and the following results were obtained.

- Kochary Embankment Dam is a heterogeneous embankment dam with a clay core which located in Golpayegan city of Isfahan province.
- The axis of this dam is located in a shallow and narrow valley that its walls have moderate to high slope and the valley in the dam axis is V-shaped.
- In sealed off condition, the area of the permeable foundation of the dam project is equal to 802 m^2 and its seepage is equal to 750,000 cubic meters per year. In other words, the average seepage per square meter is equal to about 935.16 cubic meters per year.
- Since the ratio of the volume of water seepage to the reservoir volume is equal to 34.7%, it can be concluded that seepage through the dam foundation economically is a problem.
- After the construction of sealing trench, the area of permeable foundation is reduced to 502 square meters and thus the average seepage per square meter reaches to 82.27 cubic meters per year. The seepage through the dam foundation reaches to 41300 cubic meters per year and the ratio of the seepage volume to the reservoir volume reaches to 1.91 percent which is an acceptable value.
- By constructing sealing trench, the seepage through the Kochary Embankment Dam foundation will reach to 35200 cubic meters per year and the ratio of the seepage volume to the reservoir volume will be equal to 1.63% which is an allowable value.

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