



Role of geological structures in seepage from Lar dam reservoir

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Abstract

The main objective of this paper is to estimate the water seepage from Lar dam reservoir based on a combination of the geological structure study results and identification of the flow conduits in the right bank of the reservoir. From the beginning of impounding the dam in 1980, heavy seepage was observed at two karstic springs, Haraz and Galugah, located about 9 km downstream of the dam. During the first impounding, the discharge of the Haraz spring abruptly increased from 0.5 m³/s to around 5 m³/s. The results of piezometers and dye tests indicate that seepage occurs mainly through the right abutment of the dam where there is a structural wedge between the north dipping North Tiz Kuh and the south dipping Lar Valley faults. F1, F2, and F3 faults are the most important faults in vicinity of the structural wedge. Based on the dye test results, the North Tiz Kuh and F3 faults along which caves No. 1 and 2 are formed are regarded as two isolated conduits for seepage and conveyance into Lar Valley Fault at downstream of Lar dam. After identifying the conduits, water seepage from the Lar dam reservoir has been calculated using finite element method. According to the results of numerical method, when the reservoir water level is at 2485 m a.s.l, the average of water seepage is around 8.51 m³/s (this amount of water is related to the seepage along the Lar Valley Fault). The average discharge of springs downstream of the dam has been used to verify the numerical method. The results show a very close relation between estimated and observed discharge.

Keywords Lar dam · Structural wedge · Karstic conduit · Seepage

Introduction

The karst nature presents a great variety of risks associated with any kind of human activities. Construction of large structures in karst as dams, reservoirs, and hydropower tunnels is particularly sensitive and risky task (Milanović 1997). Seepage from dams has been reported in numerous dams in karst areas (Zou et al. 2017). Solution activity forms conduits of unpredictable dimensions and geometry whose permeability is often measured in centimeters or meters per second (Zhao et al. 2014). In most cases, the seepage occurs during the first impounding and reservoirs may fail to fill despite an extensive investigation program and sealing treatment (Karimi et al. 2005). The main causes of seepage at karst dam sites are the non-homogeneous

nature of the karst formations, inadequate data, and limited investigation due to time and cost limitations (Raeisi and Kowsar 1997). The high permeability zones are local, representing a small percentage of the total karst area. These permeable zones generally form due to diagenetic features such as dissolution and leaching out through pore channels and structural features especially joints and faults (Raeisi and Laumanns 2003). The maximum leakage from reservoirs in different karst areas of the world has been reported by Milanovic (2000).

The uncertainties of karst pattern have been classified into natural, model, parameter, data, and operational ones. Natural uncertainty is associated with the inherent randomness of natural and structural processes (Aalianvari 2017). Model uncertainty reflects the inability of the model to accurately represent the system's true physical behavior (Chang et al. 2017). Models ranging from simple empirical equations to sophisticated computer simulations are used (Koltuk et al. 2015). Parameter uncertainties result from the inability to quantify accurately the model inputs and parameters (Zheng et al. 2017). Data uncertainty includes measurement errors, non-homogeneity of data, and an inadequate representation of the data sample due to time and cost limitations. (Yen and Tung 1993).

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The main objective of the work described in the present paper was to study the structural geology of Lar dam to identify the conduits responsible for discharge from the dam. After this, based on the dye test results, the water flow from the reservoir was estimated using a finite element method (Geostudio Software).

Lar dam

The Lar dam is located in distance of almost 110 km in north-east of Tehran on southern slope of Alborz mountains in Iran (Fig. 1). One of the major aims for building the Lar Dam was to supply part of Tehran and its adjoining rural areas drinking water and the production of electric power. This dam was exploited in 1980, but it did not meet the requirements due to lack of water preservation and water seepage in dam base-ments, according to former designed program. However, from the predicted volume of reservoir, only about 100 million m³ (MCM) is recoverable that is very different from 418 MCM primary purpose of the project.

Geology

The Lar valley in the vicinity of Lar dam is situated mainly in Mesozoic (Jurassic, Cretaceous) carbonate rocks. Tiz Kuh limestones are regional distributed to the Tiz Kuh Mountain, south of the dam and the Dombak Kuh Mountain, west of the Delichay River. Because of joints and fissures, Tiz Kuh limestones show a relative high permeability. Tiz Kuh limestones are underlain by Lar limestones which are heavy karstified. The lowest Formation is Shemshak shales which represent the impermeable rocks. The geological map and cross section of dam is show in Fig. 2.

From the beginning of impounding (May 1980), heavy seepage was observed at two karstic springs located about 9 km downstream of the dam.

Complementary grouting of the grout curtain, based on extensive exploratory work was carried out from 1983 to 1989. Despite the grouting of 10,000 tons of cement and the filling of two large karstic caverns discovered during drilling, no improvement was obtained, and grouting work was interrupted in 1989. Various studies were carried out after



Fig. 1 The location of Lar dam on Iran topographic map. Blue quadrangle indicates Lar dam area

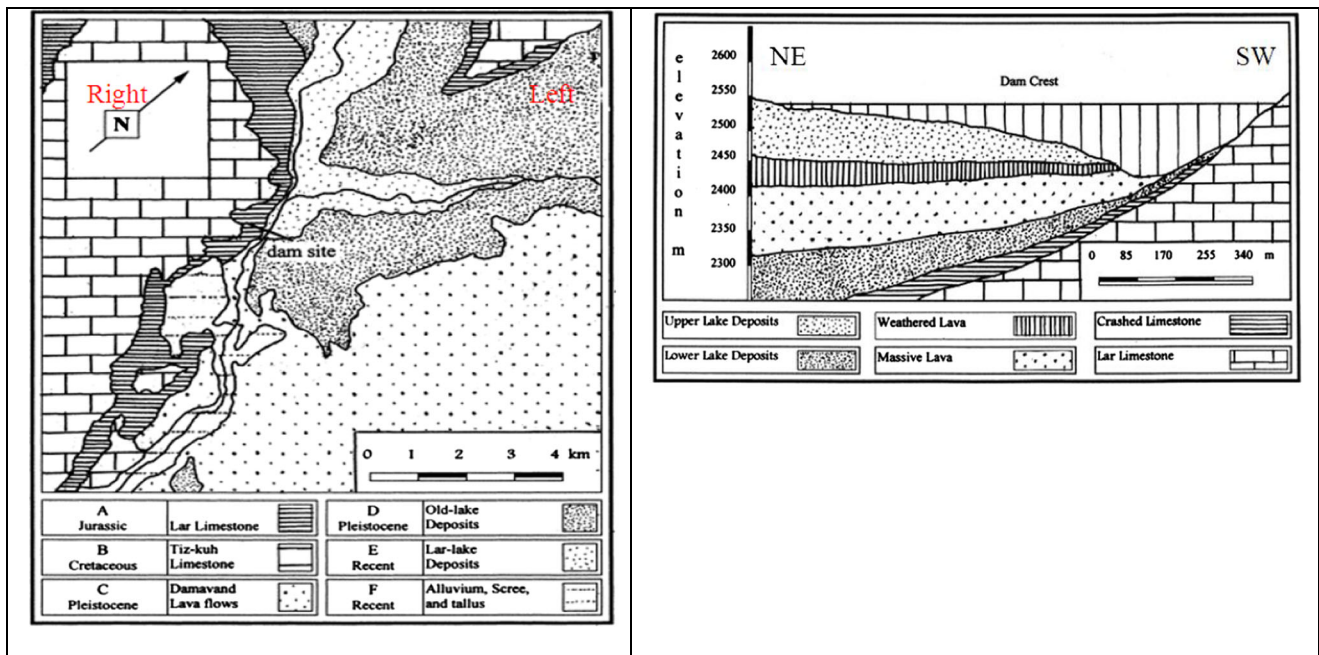


Fig. 2 Geological map of Lar dam (left) and cross section of dam foundation (right). (Uromeihy 2000)

the failure of grout curtain improvement, the last and most comprehensive one being these by SETEC in the years

1980s. None of such studies could unequivocally assess the seepage locations and mechanisms (Aalianvari et al. 2013).

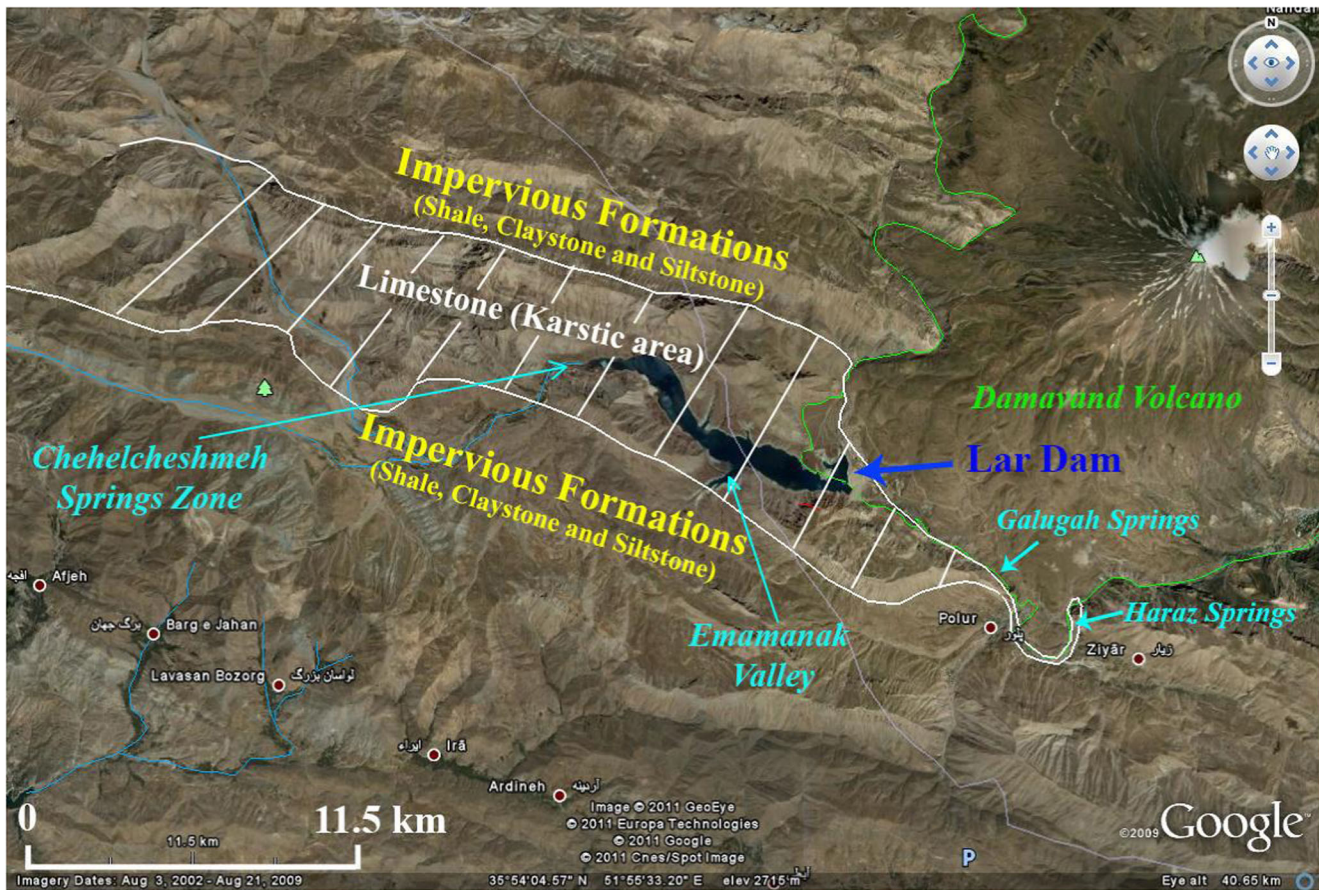


Fig. 3 Limestone area at the Lar basin which as a critical area plays a significant role in seepage and karst development

Structural elements especially faults are one of the most important features in karstification. The main goal of this paper is determination of role of geological structures especially faults in seepage from the Lar dam reservoir. For this propose, based on folded and fault structures, a structural model justifying seepage will be provided.

Morphology of dam area

From morphological point of view, all heights range from 3200 to 3900 m a.s.l except Damavand Mount which is 5671 m a.s.l. The constituent rocks of the basin include impermeable shale, sandstone, and siltstone of Shemshak Formation so that it disconnects Lar Reservoir and a larger area of it with the adjacent basins from hydraulic point of view (Fig. 3). Based on the available topographic maps, there is not a deeper valley than Lar. Therefore, waters are drained towards the Lar River as the deepest drain one of the region. Thus, water has been channelized along the old and new rivers downstream of Lar Dam. The rivers pouring into Lar Reservoir are Dalichay, Sefidab, and Lar (Chehel Barre and Khoshke Lar rivers).

Although, due to the morpho-structural conditions before activity of Mount Damavand the former base level of the Lar River was deeper than the present condition (present: 2436, previous: 1950–2050 m), lake deposits have been accumulated in the passage of long time because of the natural dams built up on the river as a result of different eruptions of Damavand Volcano. The lake deposits are now as high as 2710 m a.s.l and as thick as 400 m and 537 m measured on the upstream. These deposits locate on limy formations and seepage in these limy units caused to form sinkholes in the deposit (Fig. 4).

The dam site valley is symmetrical and the dam foundation on the right abutment consists of the steeply sloping limestones of Lar Formation, and the left abutment includes gently sloping erodible upper lake deposits, magma, and lower lake deposits.

Dam site hydrogeology

The dam site area is composed of carbonate rocks, Lar and Tiz Kuh formations, on the right bank and lake deposits plus Damavand lava on the left bank.



Fig. 4 Distribution of sinkholes in vicinity of Lar reservoir in the lake deposits. Circles indicate sinkholes

The carbonate rocks belong to Jurassic and Cretaceous formations, Lar, Tiz Kuh and Dalichai formations. Such limestone is generally karstified. In addition, due to folding and faulting, such rocks are fractured and permeable.

The lake deposits are mainly composed of silt and clay with some sand and gravel lenses. The general permeability of this unit is expected to be low except for gravelly zones which are high.

The ground water level was about 200–300 m below river bed in the area between dam axis and Emamanak valley (right bank of reservoir, Fig. 3), about 2100–2200 m a.s.l. At Chehelcheshmeh which is located upstream of Emamanak valley, the ground water level is at the river bed. It can be concluded that there is deep karstic system between Emamanak valley and the dam axis. But groundwater regime is normal between Emamanak and Chehelcheshmeh. Haraz spring which is the biggest spring in the area is located about 8 km downstream of the dam axis. Within the first filling of the reservoir, the discharge of the Haraz spring was suddenly increased from 0.5 m³/s to the average of 5 m³/s.

Several sinkholes and depressions have been observed before and after impounding in the reservoir area. All sinkholes have occurred in the lake deposits. The sink holes with large dimensions, at least 10 m diameters, occurred across a large

thickness of deposits, approximately 200 m, and most probably related to karstic cavern in the underlying bedrock.

The sinkholes with smaller size have occurred after reservoir impounding. Such holes are not connected to karstic voids in the underlying rock. They are most probably due to piping through more pervious layers of the lake deposits as for instance old alluvial channels.

Structural geology

Lar Dam is located on the south slope of Alborz and on the southwest flank of Mount Damavand. Figure 5 shows the structural map of dam area and the most important faults that can affect it.

As mentioned earlier, Lar area is located in the central Alborz. In the studied area, the general trend of the faults and folds is almost in east-west direction to northwest-southeast. This indicates that the main axis of the greater stress must have been roughly in north-south direction during the formation of these structures. The most important faults within the region concerned for tectonic studies are Mosha, Lar Valley, and Sefidab faults. These faults are active faults that due to large distance to the dam do not affect in seepage.

There are also minor faults in the investigated area near the Lar Dam, which are important from viewpoint of engineering

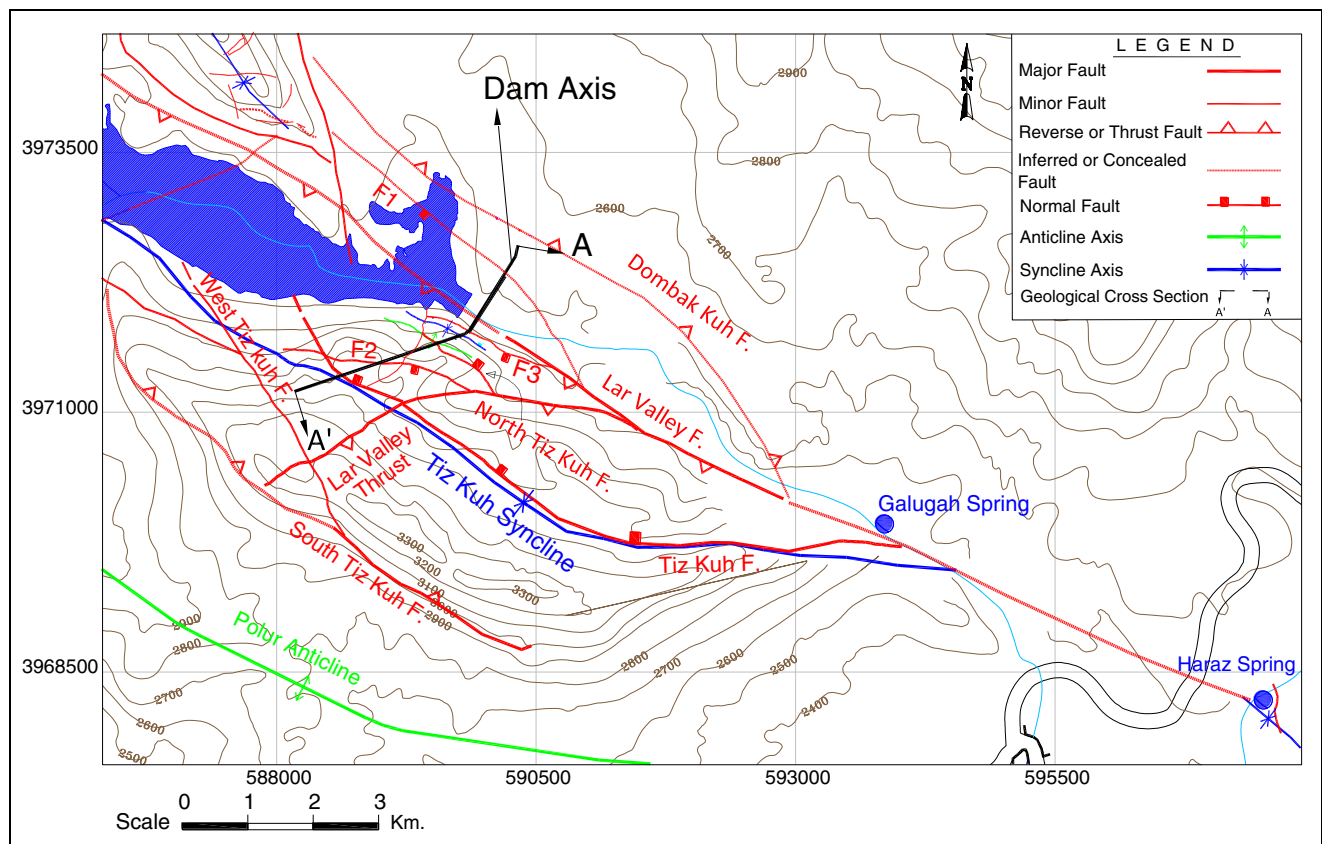


Fig. 5 Structural map of the dam area

geology and seepage. Tiz Kuh, North Tiz Kuh, Lar Valley thrust, F1, F2, F3, and Dombak Kuh faults are among the most important minor faults. Description of the most important faults that play main role in seepage from Lar dam reservoir is presented hereafter.

Tiz Kuh Normal Fault (T.F)

Tension joints and normal faults generally develop parallel to the folds axis. North dipping Tiz Kuh Fault is parallel with Tiz Kuh Syncline axis. The fault is responsible for a topographical

depression towards north (Figs. 5 and 6). Based on the tracing tests, this fault does not play any role in seepage at present. Tracing tests have shown that there is not any seepage towards the core of Tiz Kuh Syncline. This interpretation, although true, does not mean that there is no such potentiality for seepage towards the core of Tiz Kuh Syncline through Tiz Kuh Normal Fault, but it means that in the present condition and in the tracing test conducted in F2 Borehole, water escapes towards the closer channel with higher hydraulic gradient (Fig. 7). In case of a successful subsurface sealing, water may escape through Tiz Kuh Normal Fault or other faults that run parallel to it.

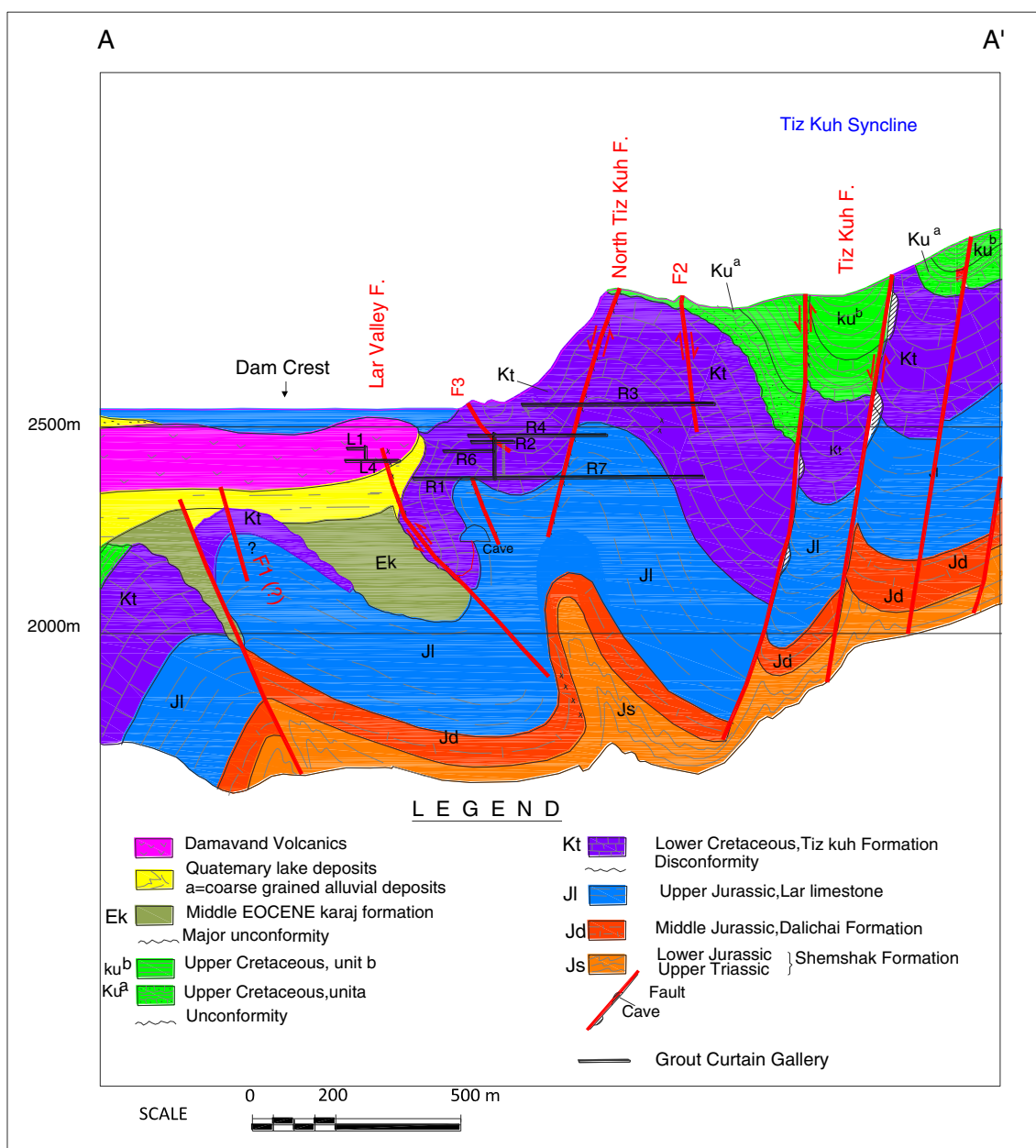


Fig. 6 Geological-structural cross section along Lar dam axis (after SETEC Consulting Engineers 1994c, with little changes). Line AA' has been shown on Fig. 5

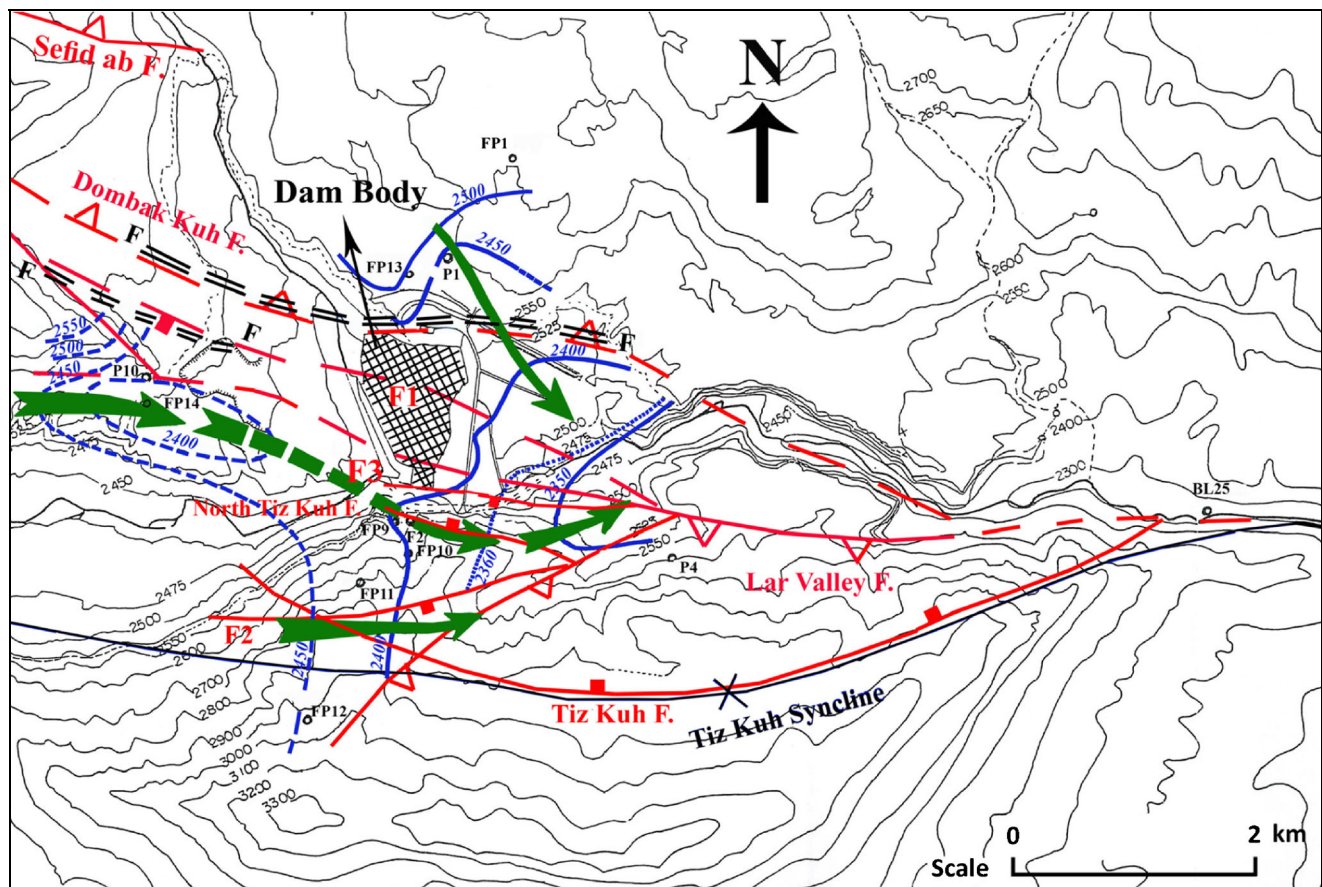


Fig. 7 Piezometric scheme at EL. 2250 m, Summer 1992, which is shown on SETEC Consulting Engineers, 1994 (a). Faults, red lines, were drawn based on the present study. Parallel black dash lines show

the faults determined by the combination of magnetotelluric and geoelectric studies. Blue thick lines show groundwater contour lines. Green arrows show the direction of groundwater

North Tiz Kuh Fault (N.T.F)

North Tiz Kuh Fault is relatively short but effective in facilitating seepage. This normal fault has been developed with a northward dip in the core of an anticline with short wave length immediately north of Tiz Kuh Syncline (Fig. 6). As seen on Fig. 6, this fault accounts for the falling of its north block and, possibly, a displacement along this fault has triggered a landslide in the past forming one of the natural dams in the Lar Valley. North Tiz Kuh Fault is well recognized in the boreholes of R3 Gallery with a crushed and brecciated zone. Together with Lar Valley Reverse Fault, North Tiz Kuh Fault has developed a structural wedge on the right abutment of Lar Dam which plays the principal role in seepage from the Lar Reservoir. This wedge is dealt within further detail in the following sections. Based on the piezometric map prepared by SETEC Consulting Engineers (1994a), groundwater vector lies along this fault which indicates the effect of the mentioned fault in seepage from the reservoir (Fig. 7).

F1 Fault

F1 Fault is another normal fault at the studied area which has been identified by geophysical investigations (SETEC Consulting Engineers 1994b). The effect of the mentioned fault is not visible on the ground surface, even on the aerial photos taken before construction of the dam. The mentioned fault is covered with alluvium so it is shown as a concealed or probable fault on the fault map (Fig. 5). It is demonstrated as a reverse fault along the axis of a covered anticline (Fig. 6). Its mechanism and dip do not have a determining role in these investigations. What is important about it is its role in seepage which is shown on the piezometric map (Fig. 7).

F2 Fault

This fault lies south of North Tiz Kuh Fault and subparallel with it in the north flank of Tiz Kuh syncline. This south dipping normal fault extends east to reach Lar Valley Thrust (Figs. 5 and 7). The crushed zones resulting from the activity

of this fault have been observed in some boreholes of R3 gallery. Morphological indications suggest that its dip is towards south, but subsurface indications, in the boreholes, suggest a subvertical to northward dip. It is one of the faults facilitating seepage as is clearly shown in the piezometric map (Fig. 7).

F3 Fault

This is another normal fault of Lar Dam area extending parallel with the North Tiz Kuh Fault and at the south flank of a local syncline on the right abutment of the dam (Fig. 6). This fault has been encountered in some boreholes of R2 gallery (SETEC Consulting Engineers 1994c). F3 Fault can be one of the faults effective in seepage on the right abutment considering its location and normal mechanism. Many transverse faults on the right abutment of the dam cross this fault and therefore can convey water from the reservoir to this fault (Fig. 8).

Lar Valley Fault

With a length of about 24 km, this southwest dipping reverse fault is characterized by WNW-ESE strike, dominantly N60W. The best location for recognition of it is on the right bank downstream from the dam where the Tiz Kuh Formation,

Orbitolina limestone of Lower Cretaceous, is thrust from south over the lower-middle part of Karaj Formation, including green tuffs, Andesitic-basaltic of Eocene, and Ziyarat Formation, including Numolitic Alveolina limestone; conglomerate and gypsum in the lower part belong to Paleocene-Eocene, on the north. At this place, a morphological feature, saddle, helps identify the Lar Valley Fault easily (Fig. 5).

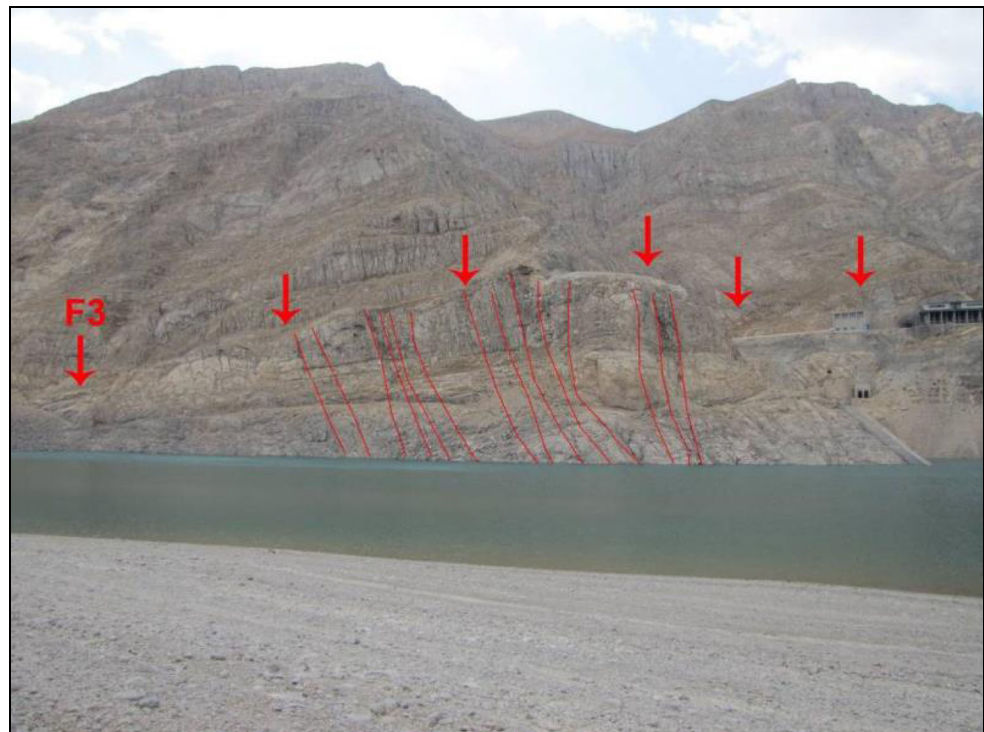
Lar Valley Fault has been well identified in some boreholes of R1 and L1 Galleries with crushed and brecciated zones. Considering the evidences in these boreholes, the fault dips 45–50° south (Fig. 6). Based on the crushed zone identified in the beginning of L1CH02 Borehole in Damavand volcanic lava, it can be stated that firstly, Lar Valley Fault has at least cut Quaternary lava and therefore is a Quaternary fault and, secondly, its dip becomes steeper towards the ground surface, 75–80°. According to Fig. 6, Lar Valley Fault is the main conduit for seepage from the Lar dam reservoir.

Structural model

Based on what was stated so far in this paper, the structural model of the region in connection with seepage can be defined as follows (Figs. 7 and 9):

Lar Dam is located in the south part of Central Alborz at the southwest slope of Damavand Mountain. The main structural trend in the study area is NW-SE, and all axial trends of the folded structures and major faults in the

Fig. 8 F3 Fault on the right bank of the reservoir. Joints and the numerous transverse faults cross the F3 faults. These structures convey the water to F3 Fault, and F3 Fault conveys the water to Lar Valley Fault (view directed to south)



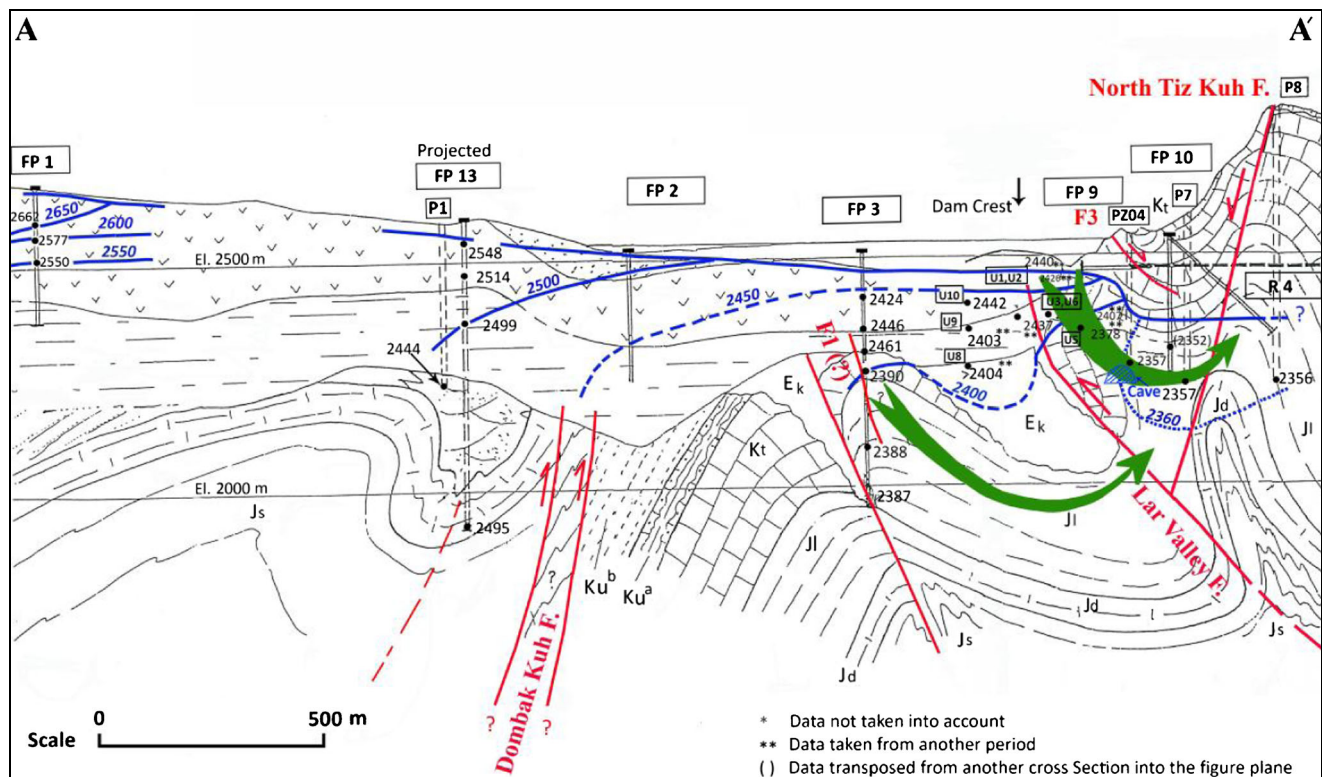


Fig. 9 Piezometric cross section along dam axis, AA' line in Fig. 5, during Summer-Autumn of 1992 (after SETEC Consulting Engineers, 1994 (c), with little changes). Faults, red lines, were drawn based on the present study. Blue thick lines show ground water contour lines. Green

arrows show the direction of ground water; note the water flow direction into the structural wedge formed between North Tiz Kuh Fault and Lar Valley Fault

region follow this trend. The most important folded structures at the studied area are Polur anticline, Tiz Kuh syncline, and Sefidab anticline. Shemshak impermeable formation constitutes the cores of Polur and Sefidab anticlines. Between the two mentioned anticlines in the core of which lies the impervious Shemshak Formation, Tiz Kuh Syncline as a structure that had potential to develop karstic features, in the core of which lie Dalichay, Lar, Tiz Kuh, and Upper Cretaceous limestone formations, plays the main role in seepage. The syncline has double-plunged towards northwest, end of the reservoir, and southeast, Haraz Springs, and the reservoir lies either on its north flank or on the core of this syncline. Therefore, this structure is a structural wedge apt to develop karstic cavities and phenomena at the area. This area is demonstrated as critical area on Fig. 3. This area is limited to Sefidab Fault on the north, Shemshak Formation outcrops on the hanging wall of Sefidab fault, and to north flank of Shemshak Formation on Polur anticline on the south. Among the foregoing major folded structures, there are also minor folded structures almost all with strikes parallel to the trends of the major ones (Fig. 6).

There were several reverse and normal faults with trending sub-parallel to the folded structures at the area of the reservoir and the reservoir banks. The most important of these faults are

DombakKuh, Lar Valley, Lar Valley thrust, South Tiz Kuh Reverse faults and Tiz Kuh, North Tiz Kuh, F1, F2, and F3 normal faults (Figs. 5 and 7).

The development of karstic phenomena and conduits along the mentioned faults is very likely considering their activity in limestone formations and crossing many minor faults. Therefore, all of the mentioned faults may be responsible for seepage. But all of the investigations performed so far, tracing tests, piezometers, sinkholes, excavations, drillings etc., indicate that water escapes mainly from the right side of the dam where there is a structural wedge between the north-dipping North Tiz Kuh Fault and the south-dipping Lar Valley reverse fault, which seems to pass water based on the introduced structural elements as well as the piezometric map and geological cross section (Figs. 6 and 7). However, the piezometric map also shows water escapes from the left bank, around Dalichay River, towards Dombak Kuh, F1, and Lar Valley faults (Fig. 7). Therefore, Lar Valley Fault is considered as the main seepage conduit and the other minor faults and fractures convey water from the reservoir area into this conduit.

It should be mentioned that Lar Valley Fault downstream from Galugah Springs is not traceable on the ground surface. On the other hand, the presence of the Lar Valley Fault with its geometry at Haraz spring location is not clear and definite. Therefore, downstream from Galugah spring, water escaping

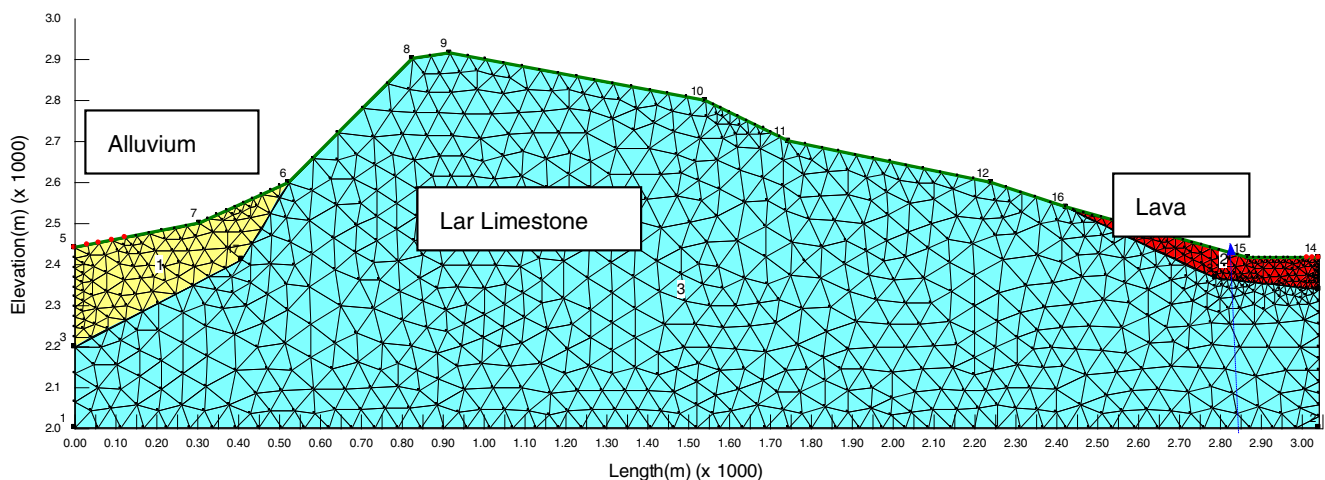


Fig. 10 Geostudio model with geological units

to Haraz spring should take place through the existing fracture system at this location. In any case, however, the wedge shape of Tiz Kuh syncline does not allow the development of springs elsewhere in Haraz Valley. Hence, there is no other pathway except the Lar Valley Fault and the fracture system downstream from Galugah spring for water after escaping the reservoir through underground conduits.

Estimation of water seepage from Lar dam reservoir

There are different methods to calculate water seepage from the reservoir, such as analytical and numerical methods. In this research, water seepage from the reservoir was estimated using a finite element method.

A finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for differential equations. It uses variational methods (the calculus of variations) to minimize an error function and produce a

stable solution. Just as many tiny straight lines can be used to approximate a larger circle, FEM encompasses all of the methods that employ many simple element equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain (Geo-Slope International Ltd. 2006). Numerical simulation of water flow and transport has become a standard tool in water resource management. In contrast to analytical solutions, numerical simulations can easily be adopted to accommodate irregular geometries, spatial variability in hydraulic properties, and boundary conditions that evolve over time (Berkowitz 1993).

In this paper, a numerical finite element model implemented in the SEEP/W software package (Geo-Slope International Ltd. 2006) is presented. It is capable of predicting the water inflow and estimating the height of the seepage face in an excavation. The SEEP/W model is able to analyze different flow conditions such as saturated/unsaturated flow and a confined/unconfined aquifer in a two-dimensional situation. To calculate the amount of water seepage from dam, different geological sections were prepared. In order to calculate the

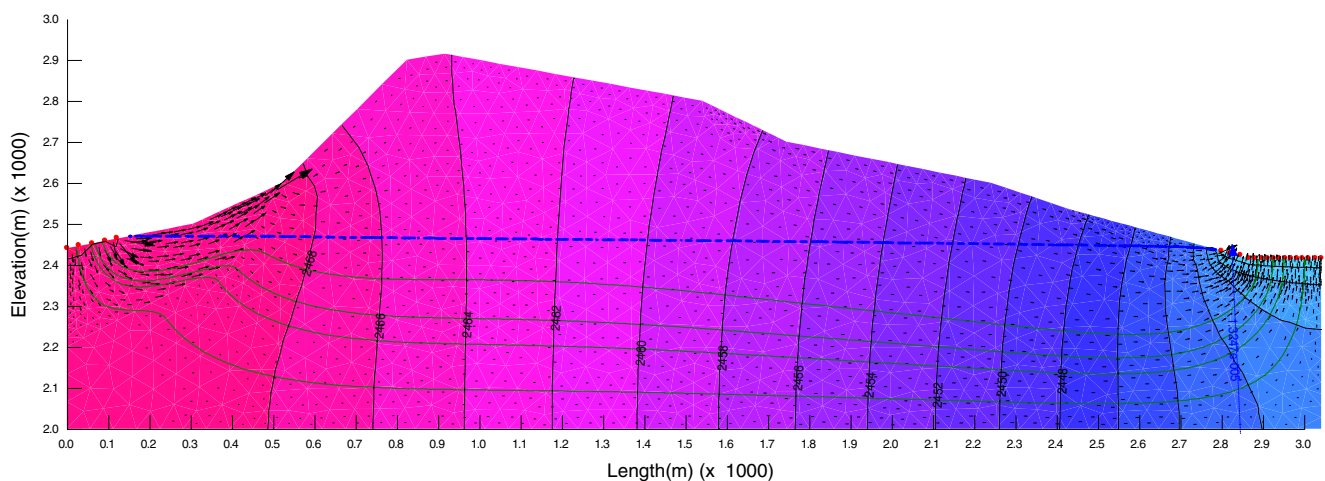


Fig. 11 Flow lines and iso potential line

Table 1 Results of seep/w modeling

Estimated Seepage(m ³ /s)	Normal water elevation of reservoir (m a.s.l)
7.3	2470
7.50	2475
7.99	2480
8.51	2485

water seepage from dam reservoir and abutments, a few geological sections were prepared based on the results of structural geology and conduits (Figs. 10 and 11).

The seepage sections are located at the limestone rocks and along the sinkholes that have the highest seepage potential. The FEM model has been generated for each section. The results of modeling for various levels of water reservoir are shown in Table 1. The seepage results presented in Table 1 are the total seep from the reservoirs and dam abutments.

Statistical investigation show that about 83% of seepage has been done from right abutment and 17% flow from left abutment.

Verification of results by the downstream spring discharge

The general direction of groundwater flow is mostly towards the local base of erosion, parallel to the strike. Karst water discharges as springs or flows into the adjacent alluvium aquifer where a direct connection exists between the alluvium and the karst Formation.

Measurement of water flow in the springs indicates the direct relation of the outlet water from the springs and the water level of the reservoir. Measurement discharges of springs are shown in Table 2.

In order to verification of numerical modeling results and actual water seepage from reservoir, the spring discharges, calculated seepage, and normal water elevation has been shown in the Table 3.

Table 2 Measurement discharges of springs

Spring discharge(m ³ /s)	Normal water elevation of reservoir (m a.s.l)
6.2	2470
8.2	2475
8.5	2480
8.75	2485

Table 3 Comparison between spring discharges, calculated seepage, and normal water elevation

Calculated seepage (m ³ /s)	Spring discharges (m ³ /s)	Normal water elevation of reservoir (m a.s.l)
7.3	6.2	2470
7.50	8.2	2475
7.99	8.5	2480
8.51	8.75	2485

Results from the numerical modeling method and observed water discharges from the springs have been compared. Results show that because the location of geological sections and most of parameters regulating groundwater inflow into tunnels have been considered in the method, the results from the method are very close to the observed water discharges.

Conclusion

1. There are lacustrine deposits with a considerable thickness, about 400 m, in the dam reservoir which indicates that an old natural dam has been occurred in this area by Damavand lava (Quaternary). Appearance of many sinkholes in the deposits indicates development of Karstification in lower limey units. Lar Dam is located on a series of anticlines and synclines with short wave length on the north limb of Tiz Kuh Syncline in the core which lie Delichay (Jurassic), Lar (Jurassic), Tiz Kuh (Cretaceous) limy Formations. Tiz Kuh Syncline as a structure that has had potential to develop karstic features could play the main role in seepage from reservoir to Haraz and Galugah springs. The reservoir lies on its north flank and on the core of this syncline. There are several reverse and normal faults having sub-parallel trend to Tiz Kuh syncline axis at the reservoir and the reservoir banks.
2. Tracing tests indicated that there are hydraulic relationships between caves no. 2, under gallery R1, and no. 1, under borehole F2, with Haraz and Galugah springs. On the other hand, there is no hydraulic relationship between caves no. 1 and no. 2. Therefore, North Tiz Kuh and F3 faults along which cave nos. 1 and 2 have been formed are considered as two isolated conduits for seepage and conveyance into Lar Valley Fault at downstream of Lar dam.
3. The structural complex described above is the cause for the seepage from Lar dam reservoir. This structural set consists of several normal faults sub-parallel to the general trend of the reservoir inside a karstified limy area from the dam up to Galugah and Haraz springs. All of these features are located into core of Tiz Kuh syncline.

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