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Influence of Geological Structure on Dam Behavior and Case Studies

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Abstract

Complex engineering projects including large dams require extensive reconnaissance. The study of geological relationships is therefore of major importance, with emphasis on the characteristics of the geological structures. Accordingly, geologic structure affects dam site and reservoir behavior in three ways: (1) its impact on the geomechanical properties of rocks; (2) the importance of geologic structures in the identification and assessment of karst hydrogeology; and (3) its role in seismotectonic and seismic risk analysis of dam projects. Site geology and availability of various geologic data obtained from site investigation are key points in dam construction. Geological structure plays an important role in dam site geology and imposes major limitations on dam behavior during and after construction stages. This role has its own effect on major subjects such as: morphotectonics of rivers; geotechnical properties and engineering geology of dam sites; and hydrogeology of dam abutments and reservoir. The variability and complexity of geological structures regarding their tectonic situation result in different scenarios regarding dam's behavior. This chapter examines the link between geological structure and dam behavior during and after construction period by describing four dam case examples: two earth (Marun and Gotvand) and two concrete (Karun-1 and -3) dams in Iran.

Keywords: geologic structure, dam behavior, Karun-1 dam, Karun-3 dam, Marun dam, Gotvand dam, southwestern Iran

1. Introduction

Complexity of large civil engineering projects such as dams necessitates extensive reconnaissance. Particularly, the construction of dams and reservoirs in karstified rocks with known high perviousness due to dissolution faults and conduits intensifies the risk of water loss and

instability [1]. Water seepage and loss through dam foundation and abutments, especially those constructed in karstic regions lead to considerable costs, sometimes postpones dam construction targets. Although this is of less importance regarding dam instability, current experience shows that there could be a fair relationship between instability and water seepage, where fault and fracture systems are the main conduits for water flow. Thus, the study of geological relationships is of major importance, with main emphasis on the characteristics of the structural features and recent tectonic movements [2]. The structural geology has a great deal in contributing to the engineering projects, and knowledge of structural geology setting is essential for safe design of these projects [3]. A detailed study with focus on the analysis of fault and fracture systems, their activities, movement types, and position ought to be done. The evaluation of stress relationships and possible temporal and spatial deformations are also necessary.

On a regional scale, structural relationships have an important role in forming the hydrogeological properties in karst regions. Although the possibility for karstification perpendicular to the geologic structures is considerably reduced, where an anticlinal structure exists between the reservoir and the lower erosion base level [4], in young orogens such as the Zagros belt, where transverse and antecedent drainage pattern is of particular importance [5], reservoir water tightness is highly risky due to dissolution fractures and conduits. One of the structural controls in the development of drainage in modern orogens is fault and fracture systems,



Figure 1. Locations of Karun-1 dam (1), Karun-3 dam (2), Marun dam (3), and Gotvand dam (4) considered for this study.

due to actively growing of structures [6]. In the Zagros fold belt, superimposed drainage was found to be related to structural associations leading to transverse drainage pattern [7]. The position of the folded structures had a decisive role in the formation of the pre-karstic drainage network, that is, directions of the main surface outflow. As a result of the new tectonic activity, the homogeneous anticlinal structure has been fractured transversely and huge separate blocks have been formed [8]. Accordingly, challenges regarding the relationship between geologic structure and dam behavior are described and discussed for four dam cases, namely Karun-1 concrete dam, Karun-3 concrete dam, Marun earth dam, and Gotvand earth dam, which are located in Khuzestan Province, southwest of Iran (**Figure 1**).

2. General geology and seismicity

The Zagros fold-thrust belt (briefly named as Zagros mountains) being located to the northeast of the Persian Gulf extends for about 1800 km between northern Iraq and the Strait of Hormuz and comprises the deformed part of the Arabian plate following its continental collision with central Iran almost since the Miocene [9]. It is a branch of the Alpine-Himalayan Orogenic belt [10, 11]. The mountain range can be divided into two distinct zones say, the northeastern High Zagros (**Figure 2**) and the southwestern Simply Folded Belt (SFB) based on topography, geomorphology, exposed stratigraphy, and seismicity [12]. The Simply Folded Belt extends from the High Zagros Fault to the Persian Gulf [13]. Topographic highs are typical of the anticlines and synclines form the topographic lows. The existing landforms graphically reveal the geologic structure. Anticlines show remarkable regularity in relief over long distances and the rivers which cut them usually do so at sharp angles to the strike of the anticlines. The SFB is a fold belt characterized by NW-SE trending parallel anticlines and synclines and is composed of elongated whaleback or box-shaped anticlinal mountains. From a geomorphological view point, the anticlines can be divided into two sets; plain anticlines and mountain anticlines [12].

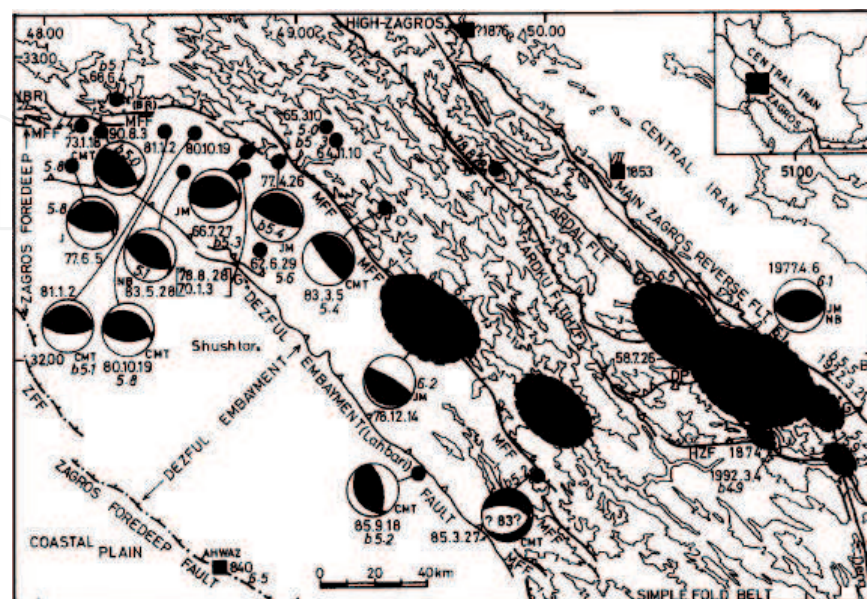


Figure 2. Seismotectonic features of the study area in the Khuzestan Province [14].

In fact, most part of the study area, that is, Khuzestan Province and the aforementioned dams are almost located in the Dezful Embayment, which is a structural unit of the SFB.

Iran can be generally divided into five major seismotectonic zones (**Figure 2**) that are subjected to destructive earthquakes excluding one (Central Iran characterized by low seismicity). It is considered as a broad seismic zone over 1000 km width that extends from the Turanian platform (southern Eurasia) in the northeast to the Arabian plate in the southwest. The Iranian plateau is characterized by active faulting, recent volcanic activity, and high density of active and recent faults. Reverse faulting dominates the tectonic mechanism of the region. Southwest of Iran, where the studied large dams are located, belongs to the Zagros Active Fold Belt from the seismotectonic point of view [14]. Seismicity in this belt correlates well with topographic elevations greater than 1.5 km. Fault plane solutions for several earthquakes consistently show high angle (40° – 50°) reverse faulting and the estimated depths range from 8 to 13 km with magnitudes that range from 4 to 6. The rate of seismicity in this zone is higher than the others, but the type of seismicity is mostly between small to moderate and seldom large. Due to its particular tectonic condition, the large earthquakes have rarely been accompanied by surface rupture in the SFB. Based on the available fault plane mechanisms of the regional events, the maximum principal stress, which is due to regional tectonic forces, strikes $N30^{\circ} \pm 5^{\circ}$ (NE–SW) [15].

3. Karun-1 dam

Karun-1 (also known as Shahid Abbaspour) is a 200 m high concrete arch dam (**Figures 1 and 3**) at nearly 52 km to the northeast of Masjid-I-Solaiman City in the Khuzestan Province. It was constructed on the Karun River with a reservoir capacity of 3139 MCM to produce electrical energy, to control flood, and to regulate water. The first impounding of the dam reservoir was in December 1976. The presence of two springs downstream the right abutment of the dam site and construction of a new power plant besides recent rock sliding on the dam abutments are the main points of discussion. Since the completion of the dam, seepage problem was a key challenging subject regarding the right abutment shear zone and downstream springs [16–18].

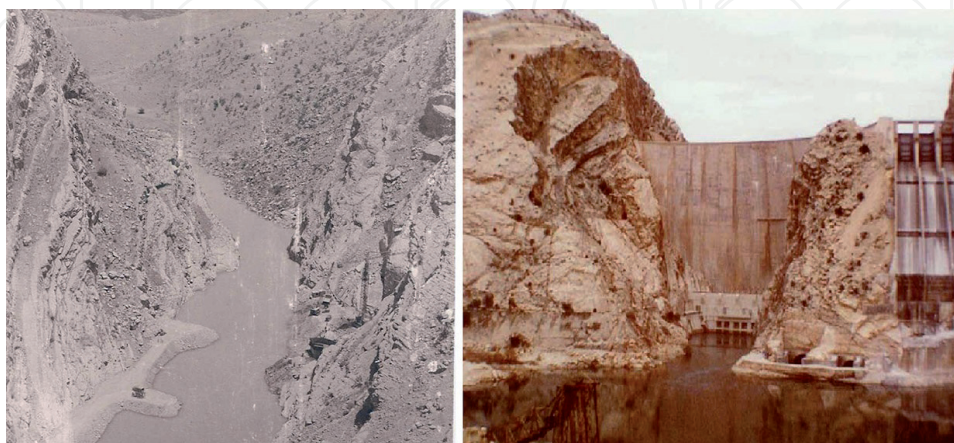


Figure 3. Upstream view of Karun-1 dam site before (left) and after (right) construction.

Some studies were later done regarding the construction of a new second powerhouse in the left abutment of the dam [19–21] and recently, rock fall on the right abutment [22, 23].

Karun-1 dam site is located on the southwestern limb of Kamarun anticline (**Figure 4**) with average bedding dip of 35° toward SW. The anticline is composed of Asmari Limestone of Olig-Miocene age. Asmari formation limestone is a suitable rock foundation for dams regarding its relatively exclusive characteristics such as rigidity and morphology. This formation constitutes a series of double plunging, asymmetrical folds with northwest-southeast trend having steeper southern flanks than the northern ones. The Asmari limestone forms the entire foundation of the Karun-1 dam. It is divided into three parts at the dam site namely, lower, middle, and upper Asmari. The dam is situated on low-karstified middle Asmari that consists of a relatively permeable zone, which in turn is overlain by an impervious shale layer. The upper Asmari limestone exposed just downstream the dam, is highly karstified [16, 18]. The anticline shows some axial plane rotation along its southeast plunge, however, its general trend is northwest-southeast as is common in the whole belt.

The region is seismotectonically very active regarding its location in the Zagros active fold-thrust belt [14]. The main faults in the region are of thrust types of which Izeh fault zone cutting across east of the region is a very known feature due to its right lateral component of movement. The Andeka Fault is the main active fault close to the dam site that is characterized by very recent activity [24, 25]. Although no major fault exists at the dam site, recent investigations for excavation of a new powerhouse identified a fault with a general NW-SE trend [20], accompanied by high fracture density. This is most probably a hidden blind fault that is expected to cut the anticline core. The geologic structure of the dam site includes bedding, joint sets, and a spectacular shear zone in the right abutment. Recent study indicated a tectonic lineament with a NE-SW trend that passes through the right abutment, which could

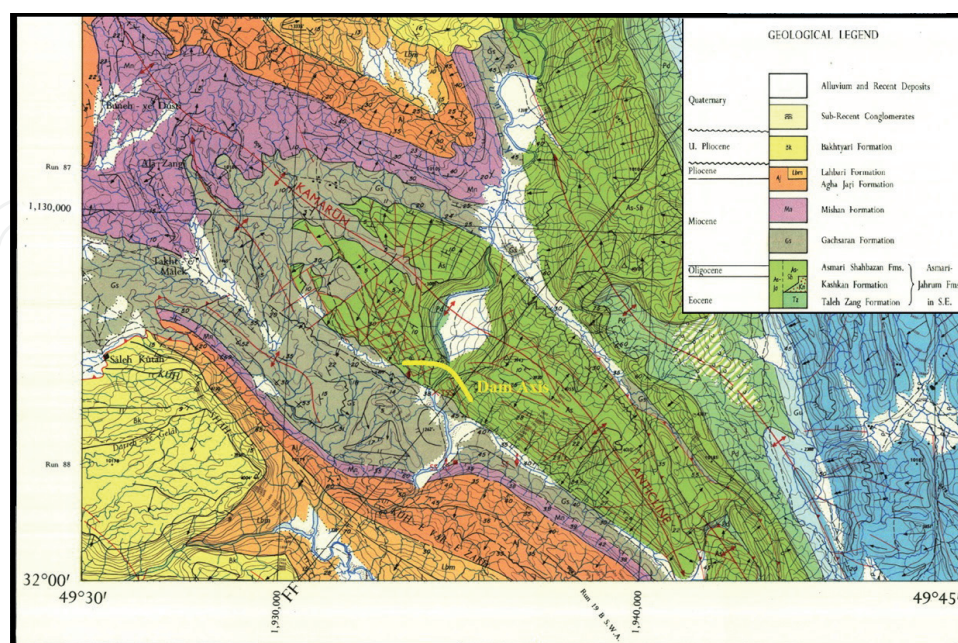


Figure 4. 1/100000 Geological map of the Karun-1 dam region [23].

be the main cause of shearing and fracturing in the right abutment [23]. The bedding plane has an average attitude of 32.5/210 (dip/dip direction) in the southwest limb (**Figure 5**) on which the dam is located and is expected to be the major discontinuity at the dam site. The southwest limb has a larger dip than the northeast one, which is characteristic of the southwestern limbs of the Zagros anticlines. It shows high degree of separation with less favorable shear signature. Three joint sets are identified at the dam site with 24/253, 21/166, and 47/038 attitudes. The joints are filled with calcite or clay and partly show slicken-lines. Their spacing is mostly dependent on strike and dip, but small changes can be seen in the joint opening of the left abutment after the excavation of the new powerhouse (No. 2 powerhouse) possibly due to blasting operation. Big or Sabz (meaning green) and Powerhouse Springs are the most significant and spectacular hydrogeological features at the dam site [18]. They demonstrate a widespread karst system in the Asmari limestone. The Zagros anticlines, particularly in the Asmari Formation, contain tension-induced, open fracturing, which has introduced significant secondary permeability to the rock. In this regard, the right abutment shear zone trend strikes along this direction that corresponds to the main regional extensional fractures and is very favorable for ground water flow. The Big Spring flows through a large karst cavern with an average discharge of 4–5 m³/s (**Figure 4**). The Powerhouse Spring discharge averaged about 0.25 m³/s. After reservoir impounding, the estimated discharge of Big Spring increased from 10 to 16 m³/s [26]. Few researches on the springs and reservoir water level fluctuations and sedimentology suggest that the springs' water passing under the foundation is independent of reservoir water elevation and depends on tail water elevation although some suggestions are against this conclusion [18].

The location of the two springs is aligned with a tectonic lineament trend SW-NE. Besides, the joint sets at the Big Spring location (**Figure 6**) shows the same general trend. This direction is parallel to the average direction of regional compressive stress in the Zagros Belt and indicates the general trend of extensional fractures forming normal to anticlinal structures

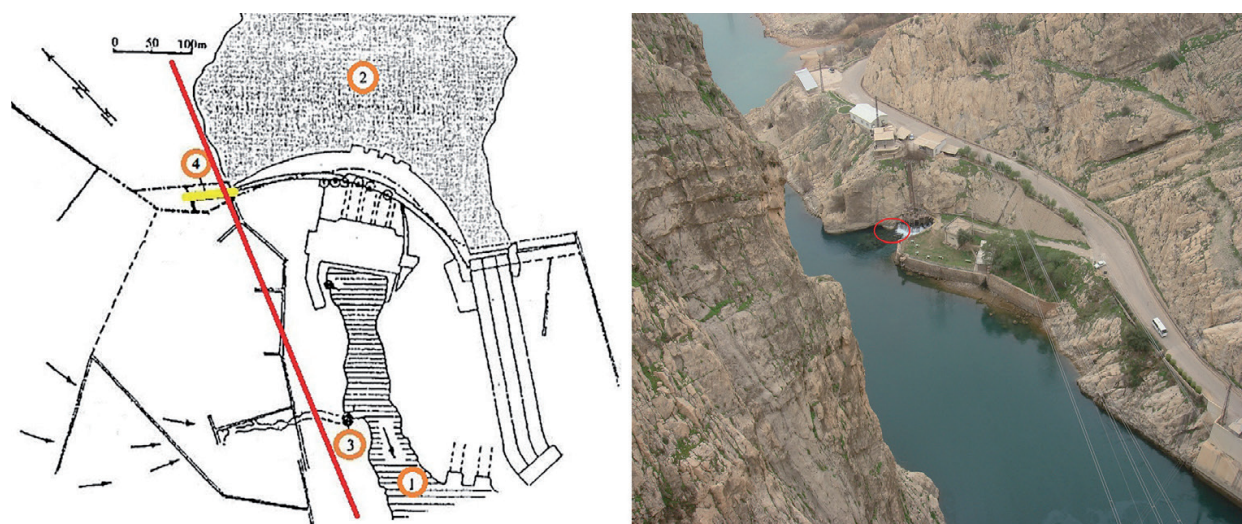


Figure 5. General layout of the dam site (left) and downstream view of Big Spring (right). The numbers in the left picture stand for: 1—Karun river, 2—reservoir, 3—Big Spring, and 4—cutoff wall.



Figure 6. A close view of Big Spring (left) and existing joint cavity (right).

pre or synchronous to folding [27]. The existing karst channel shows parallelism to the joint walls. The vertical dip of joint system on the right abutment could be another factor to support spring recharge through the reservoir area by very far upstream sources.

Another case of problem in the dam site is related to the construction of a new underground powerhouse regarding its time as the reservoir was impounded nearly 25 years before it. The newly designed structure (No. 2 powerhouse) was situated in the left bank of the dam and was excavated in the middle Asmari formation. Rock exposures displayed some signs of karstification such as open or filled cavities and small solution channels along the structural elements. Fortunately, no direct connection with tectonic elements was found in the left abutment. However, some inflow increase was observed in the newly excavated power house cavern [28], which lasted to the present.

As it was assumed basically that bedding planes were the major discontinuities of the site, the orientation of the No. 2 powerhouse was set perpendicular to the strike of bedding [20]. Fracture system in the left abutment was characterized with very wide to moderate spacing with the evidence of karstification along the joint planes. Some of the solution openings were filled with crystalline calcite and gypsum. All of this evidence supports increase of water inflow through the fractures system. The surface rock at the powerhouse slope belongs to the higher part of the Middle Asmari Formation. Based on the observations, joint sets were the main potential cause of rock instabilities of the cavern [28]. The measured permeability of rock strata was moderate to very high according to various available data with some signature of karstification. Although, Lugeon tests carried out in the geotechnical boreholes were limited to 4 LU, calculations showed a water inflow to the cavern up to 1500 l/min that necessitated creation of a gout curtain between cavern and reservoir. The last challenge related to the existing geologic structure was the potential for the mechanical initiation of a rock fall or slide during and after the dam construction. The construction phase is probably be one or two orders of magnitude higher than with natural causes [29], however, during the operation period, the phenomenon is possible as is the case for Karun-1 dam.



Figure 7. Rock sliding (in yellow) at right abutment of the dam.

Here, due to the downstream dip of bedding, which is unfavorable for a dam site, a natural potential for rock fall and slide on the dam abutments was predictable (**Figure 7**). This geological condition is of key importance since the southwestern (downstream side) limbs of the Zagros anticlines are usually very steeper than the northeastern limb due to the action of thrust faulting that affect the southwestern anticlinal limbs [30, 31]. New observations proved the subject and some rock slide and fall happened especially on the right abutment. There seems to be some flexuring along the bedding plane as well. The vertical tensional joints on the right abutment could amplify rock falling.

4. Karun-3 dam

Karun-3 is a 205 m high concrete dam constructed at 28 km to the south of Izeh City (**Figures 1 and 8**) in the southwestern Khuzestan Province. Electric power generation and flood control were the main objectives of the dam construction. Karun-3 power plant has a capacity of 2000 MW, with an average generation of 4137 GWh/y. This is a double curvature concrete arch dam, with a sub-surface powerhouse located downstream the dam and power tunnels [32, 33]. It has symmetrical shape regarding the shape of its valley. The location and alignment of the dam are limited by geological and topographical features on both abutments (**Figure 8**). The dam reservoir is 60 km



Figure 8. Upstream view of Karun-3 dam site before (left) and after (right) construction.

long with storage volume of $3 \times 10^9 \text{ m}^3$. The dam was impounded in November 2004. The presence of a hazardous slope named G2M above takeoff yard and a big downstream spring named as Abol-Ghasem Spring is of the main concern here.

The dam body was constructed on Asmari formation on the southwest limb of Keyf Malek Anticline that is surrounded by elevated anticlines including Lapeh (in the northeast) and Monghast (on the southwest) [32, 34]. The reservoir area is underlain by Pabdeh, Asmari, Gachsaran, and Agha-Jari formations. The Asmari formation limestone is the main water-bearing formation at the dam site and reservoir area with a potential for karst development similar to that discussed previously (part1) and is reported for other dam sites in the Zagros Fold Belt and in this chapter (Karun-1 and Marun dams). The Keyf Malek anticline, on which the dam lies, is mainly consisted of lower Asmari outcrops (**Figure 9**).

It is made up of interbedded limestone and marly limestone with porosity values between 1 and 15.7% that imply medium to extremely porous rocks. The limestone is generally light gray to light brownish gray, fine to medium grained, strong to very strong [32]. The bedding strikes NW-SE with low dip at the anticline crest. On the southwestern limb, the dip of layers is very steep up to 80° due SW (**Figure 10**). The northeastern limb of the anticline has a dip of about 70° – 80° . The fold axis shows a slight plunge toward the southeast ($141^\circ/06^\circ$). Regular joint sets are developed and these have consistent orientations across the project area. A major NW-SE trending fault named as Doshab Lori Fault passes within 500 m to the southwest of the dam site. Another major thrust fault cuts the northeastern limb of the anticline creating an overturned syncline between the Keyf Malek and Lapeh anticlines (**Figures 9 and 10**). The major seismically active faults in the study area [35] are presented in **Figure 11**. Some small faults cut the anticline parallel and normal to its axial trend.

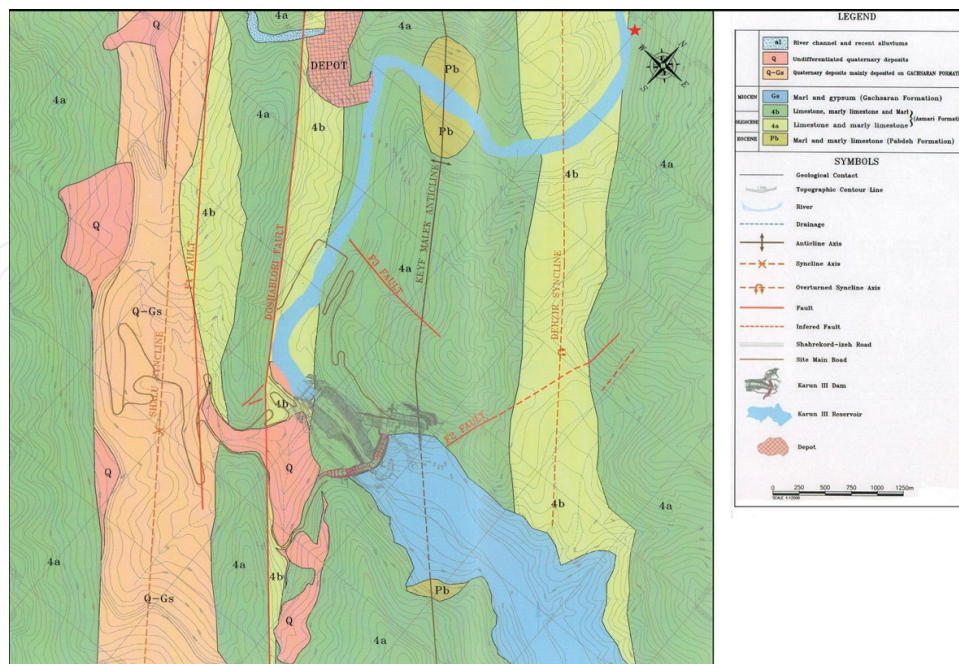


Figure 9. Geological map of the dam site area. Red star is the location of Abol-Ghasem Spring [36].

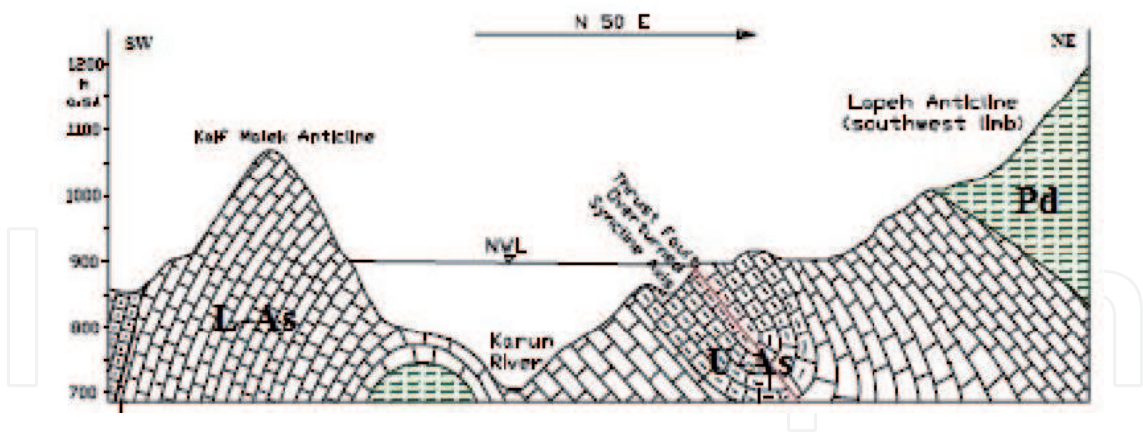


Figure 10. Geological section of Keyf Malek anticline [34].

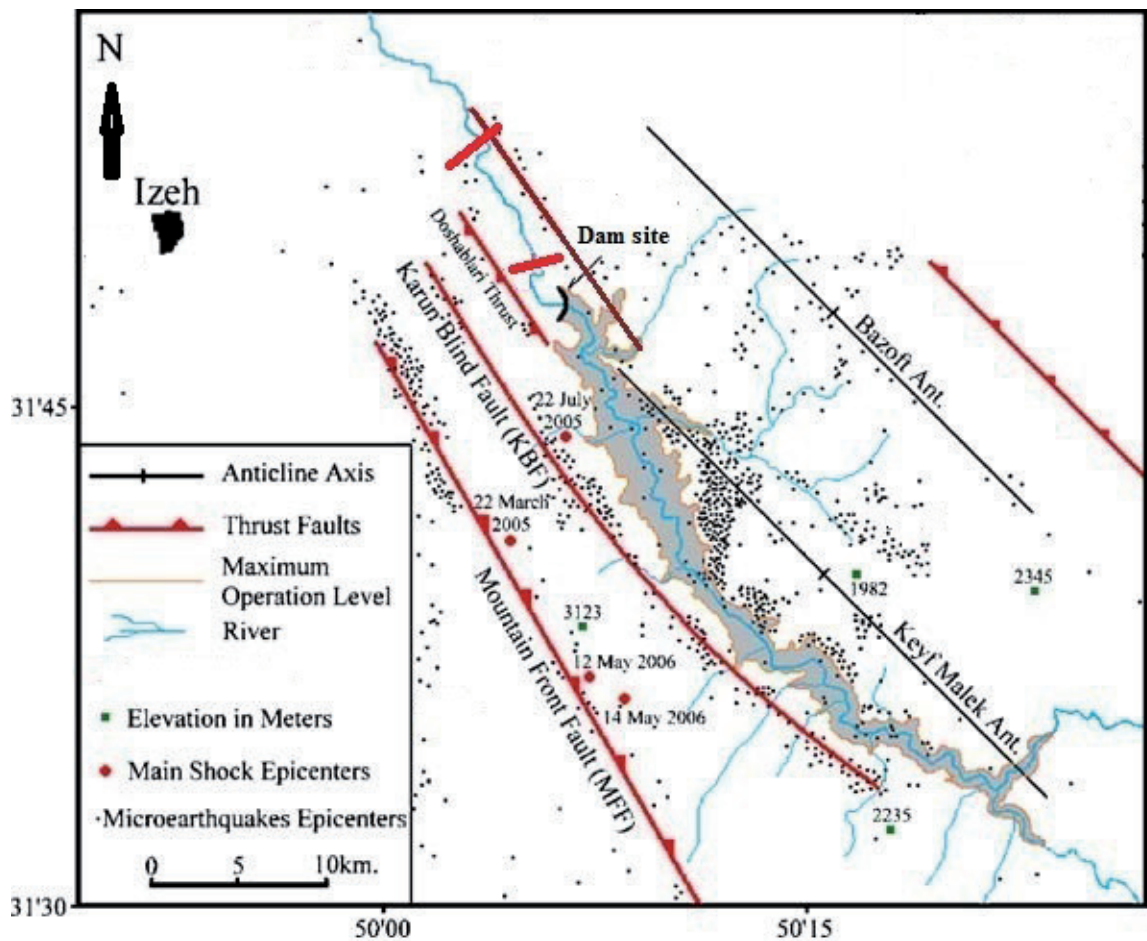


Figure 11. Regional faults and distribution of earthquake epicenters around Karun-3 dam [35].

The strike and dip of the strata vary only slightly over the dam and powerhouse sites. The bedding has a fairly flat inclination at the top of the fold, but become rapidly steeper to the west of the axis, where it generally dips 60° – 85° southwest (**Figure 12**). Mapping indicates that several strongly developed joint sets characterize the bedrock in the area.

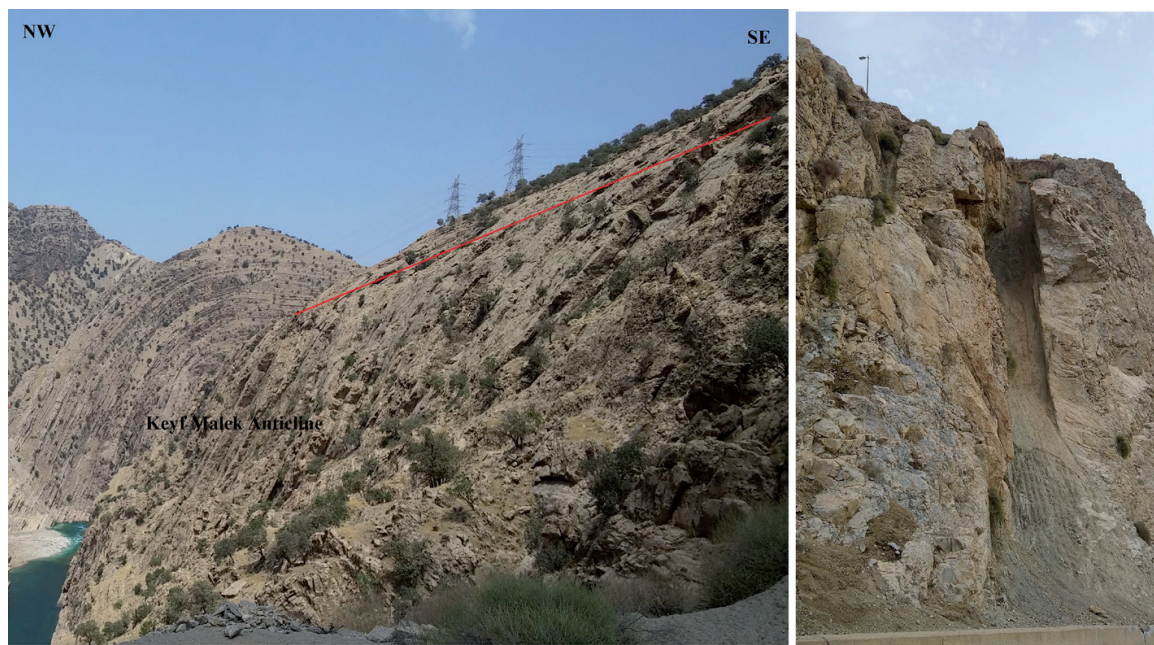


Figure 12. Downstream view of Keyf Malek anticline (left) and longitudinal fault cutting its southwestern limb (right).

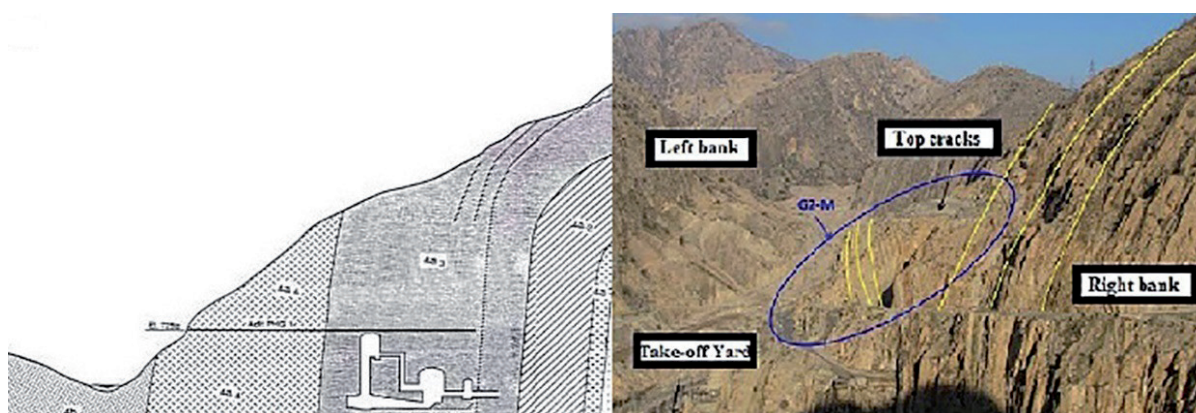


Figure 13. Geological section (left) and downstream view of G2M (right) rock mass.

As was mentioned above, instability of G2M above takeoff yard and leakage through downstream springs in particular Abol-Ghasem Spring are the main subjects of dam behavior in Karun-3 project. The rock slope, called G2M, is placed at the top of access road to the spillway on the right bank of the dam (**Figure 13**). The slope that is composed of limestone, marly limestone and marls besides developed tensional cracks created a potentially sliding mass.

Generally speaking, the slope was probably formed by displacement and collapse of the layers consequently, pushing front layers toward the river valley [33, 37]. Alternation of the competent (limestone) with incompetent (marl and marly limestone) layers at G2M slope, besides the presence of thrust faults on both flanks of Keyf Malek anticline is most probably the main reason for instability of the G2M. It is very probable that a hidden blind fault cuts the core of the anticline regarding very sudden change in dip of the bedding on the southwestern limb of

Keyf Malek anticline. This structural feature is very common in the Zagros folds specially in highly deformed and stressed regions such as Izeh fault zone in which the dam is located [36]. High fracturing of the rocks at the dam site is also a sign of the governing role of fault activity in the study area. Successive occurrence of thrust faults cutting the region and overturning of the Lapeh Anticline northeastwards is an indication of extensive tectonic deformation of the region resulted in high and dense fracturing of the Keyf Malek anticline. Additionally, the apparent break in the bedding integrity in the southwest limb of the anticline might be a sign of longitudinal faulting along its strike (**Figure 12**). It should be noted that Doshab Lory fault that runs between the Keyf Malek anticline and Mongasht anticline is a back thrust with a movement in the direction opposite to the general direction of regional tectonic transport. Since, such structures are generally an indication of fault propagation folds, intense fracturing between fore thrust and back thrust is reasonable, which is almost seen for the Karun-3 dam site. As mentioned before, Karun-3 dam site lies in the northern part of Izeh fault (shear) zone that is distinguished by a variety of thrust and dextral strike-slip faults [14] so that their interaction created a complex highly deformed and sheared geological region.

Another challenging subject in the dam region is the presence of Abol-Ghasem Spring downstream of the dam site. It is located at about 2.5 km downstream of the dam site, near the right bank of the Karun River (**Figure 9**). Its water was recharged by Lapeh anticline karstic aquifer, before impounding with varying seasonal discharge nearly between 0.5 and 1.5 m³/s, and increased to about 2.5 m³/s after reservoir impoundment. Additionally, another seasonal spring about 70 m downstream of the Abol-Ghasem Spring was changed to a permanent one after the dam impounding. It seems that the both limbs of Keyf Malek anticline are potential paths for seepage equally [34]. Karstification of the northeastern limb of the Keyf Malek anticline along with thrust faulting intensified the seepage at the spring. The presence of an overturned syncline between the two anticlines indicates intense tectonic compression in the region that could result in dense fracturing in the existing two anticlines. Transverse faults cut across the anticline that is evident through sharp and sudden change of Karun River course downstream the dam site might facilitate the occurrence of springs.

5. Marun dam

The Marun dam site is located on the Marun River in the Khuzestan Province approximately 19 km northeast of Behbahan City (**Figures 1 and 14**). The dam was commenced in 1997 and completed in 1999 with a height of 165 m, a crest length of 345 m and reservoir volume of about 1200 million cubic meters. As a rock fill dam, it is the second highest embankment dam in Iran. Its main purpose was flood control, water storage, and a total of 145 MW power generation. It also provides a dependable water resource for irrigation of 55,000 hectares of downstream farm lands. The dam site is located on the limestone of the Asmari Formation, of Oligo-Miocene age. The formation is divided into the lower, middle, and upper Asmari formation with a total thickness of 370 m. It consisted of strong limestone partly interbedded with thin layers of shale. The whole formation at the dam site is characterized by karstification evidence.

The Marun dam was built on the northeastern flank of Khaviz anticline in the Zagros fold belt. The foundation of the dam consists of thick-bedded limestone of the Asmari formation

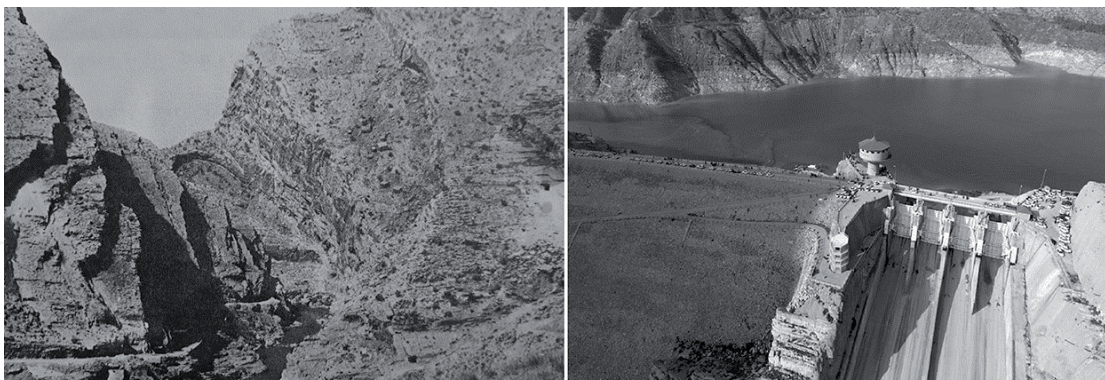


Figure 14. Upstream view of Marun dam site before (left) and after (right) construction.

with alternation of shale, marlstone gypsum, and anhydrite [38, 39]. The beds strike parallel to the dam axis trending NW-SE and average dip of approximately 35° due NE (Figure 15). The rock is regularly well jointed. Although fairly homogenous, the rock shows anisotropic permeability due to karstification of limestone. The rock strata at the site comprise a series of karstic limestones interbedded with water sensitive marls, which dip toward the reservoir. The main geological structures of the region include folds and faults aligned parallel to the main folding axis of NW-SE trend. The reservoir basin is centered mostly along the southwest flank of a broad northwest trending syncline. This feature forms a broad structural basin, approximately 9 km wide and 14 km long. At the dam site, two major joint sets are seen, the first parallel to the bedding, and the second perpendicular to it. However, a special set of

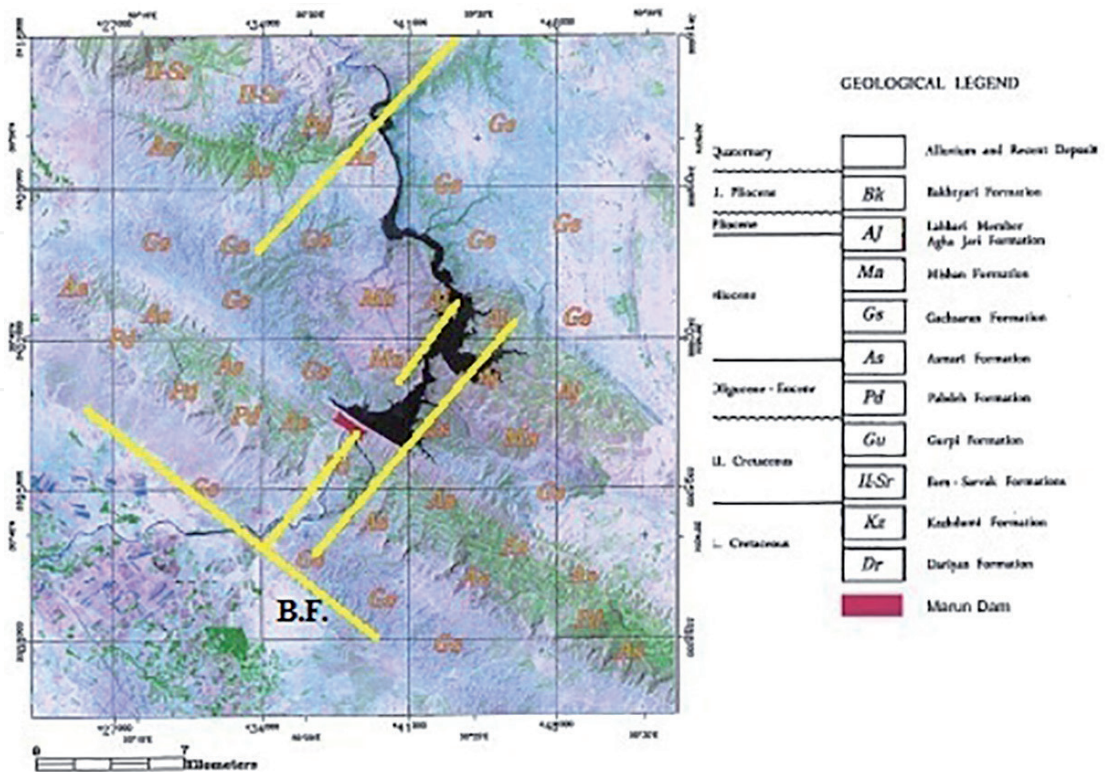


Figure 15. A general layout of Marun dam and appurtenant structures [39]. BF is Behbahan thrust fault.

fractures classified as fracture swarms [40] is also recognized here. Fracture swarms are nearly large-scale features, which dissect significant parts of the stratigraphic sequence. In the Khaviz anticline, fracture swarms are represented by faults with displacements of a few meters up to 150 m, and are associated with relative narrow damage zones with locally very high fracture frequency [40]. Three large thrust faults cut the region with a NW-SE general trend. These are named as Behbahan, Arajan, and Tashan faults [14]. A hidden fault cuts the core of Khaviz anticline parallel to Behbahan fault as well. While Karun-3 dam site lies in the northern part of Izeh fault zone, the Marun dam site is located at the southernmost part of it. The dam site is also affected by active faulting as indicated by its seismic activity especially for Tashan Fault.

The first and prominent problem encountered in Marun dam site was leakage through a diversion tunnel named as second diversion tunnel during the first impounding. Immediately after impoundment, considerable leakage was observed in the pressure tunnel (**Figure 16**) and efforts to open the stop logs failed. At the same time, an embankment was constructed and subsequent grouting controlled the leakage in the pressure tunnel. Old karst channels along a vuggy zone cut by the second diversion tunnel were reactivated and leakage occurred [39]. The total amount of water leakage through the left bank of Marun dam was about 10–15 m³/s. The unlined second diversion tunnel had a key role in connecting reservoir with karst conduit system.

The embankment was overtopped with increasing water elevation, and considerable leakage of up to 7 m³/s occurred from weak zones upstream of the plug. The major flow of approximately 4.5 m³/s was from two large solution channels and leakage around the concrete plug.

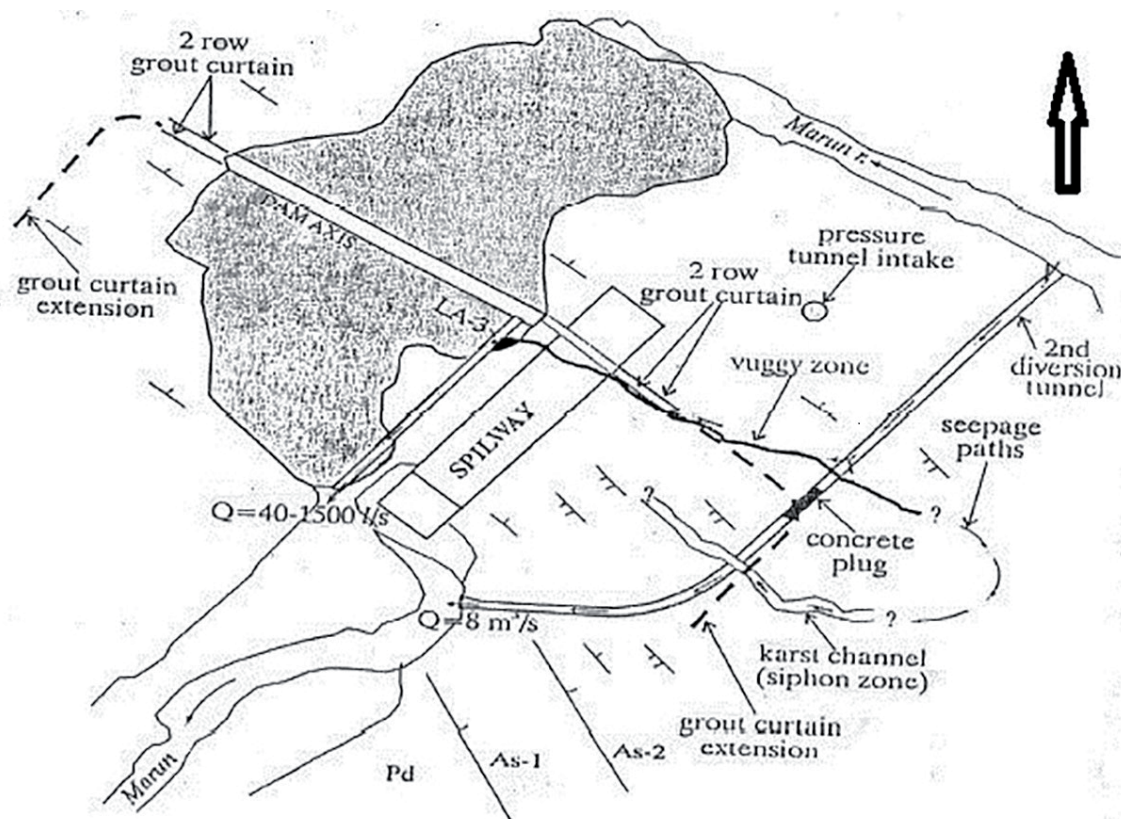


Figure 16. A general layout of Marun dam and appurtenant structures.

The remaining flow was from the access tunnel and the grouting adit ($2.3 \text{ m}^3/\text{s}$). The total amount of water leakage through the left bank of Marun dam was about $10 \text{ m}^3/\text{s}$. The water entered the fracture system upstream of the plug and passed along the fissures, washed out the marls interbeds forming large cavities. These are master cross joints traversing the dam site rocks from upstream to downstream. Water was leaking into all tunnels and the dam, and all springs received their water from the same fissure as was reported [39]. In fact, these are fracture swarms as was defined above indicating the intense fracturing surrounding faults or narrow zones with a very high frequency of fractures. These major features are major conduits for fluid flow in the subsurface at some stage that is very favorable for karst development. This is almost similar to the karstic features mentioned for Karun-1 dam (abovementioned) although it is almost visible that karstification is developed more and complete at the Marun dam site. Here, the general trend of fracture swarms is parallel to the general direction of the maximum compressive stress in the Zagros Fold Belt that produced tension-induced, open fractures resulting in significant secondary permeability to the rock. Intersection of longitudinal fractures (vuggy zone) in the Khaviz anticline with transverse fractures (fracture swarms) amplified permeability of the rock and simplified water leakage through the left abutment during the first reservoir impounding. It is very probable that seepage paths were formed along the fracture swarms parallel to the second diversion tunnel.

The second problem in Marun dam site was rock fall occurred along the left abutment recently [41]. Accordingly, stability studies and treatment are being conducted. The variation in shape of the rock blocks obtained from the joint data assessment indicates that the potential for dislodging rock blocks is medium to high. The horizontal joint sets in combination with the very steep slope face on the left bank result in blocks with a high rock fall hazard. The prevailing role of fracture system in rock slope instability at the dam site is again clear [41].

6. Gotvand dam

The Gotvand or Upper Gotvand dam as the highest rock fill dam in Iran is located in the north of Khuzestan Province (**Figures 1 and 17**). It was constructed across the Karun River in the north of Shushtar city. It is a 178 m high rock fill dam with central clay core and a crest length of 760 m. The normal reservoir level is situated at 232 m above sea level at which the reservoir reaches a capacity of 4.5 billion m^3 and around 90 km in length. The Gotvand dam has the hydropower plant with the highest energy production capacity in the country. The main purpose of the project is the production of (4250 GWh) hydroelectric energy. The impoundment of the reservoir started in July 2011 and by 2014, the reservoir water level had reached 223 m a.s.l. The main problems in the dam site and reservoir area are instability of the abutments [42] and with a minority, probable seepage potential through the foundation and abutments [43]. The dam foundation and part of the right abutment is underlain by Agha-Jari Formation of Mio-Pliocene Age (**Figures 17 and 18**). Agha-Jari lithology consists of gray, calcareous sandstone with gypsum veins and red marlstone and siltstone. Its rocks contain veins of gypsum usually associated with claystone beds. They are naturally soluble and can lead to excessive seepage. The left abutment of the dam is composed of Bakhtyari

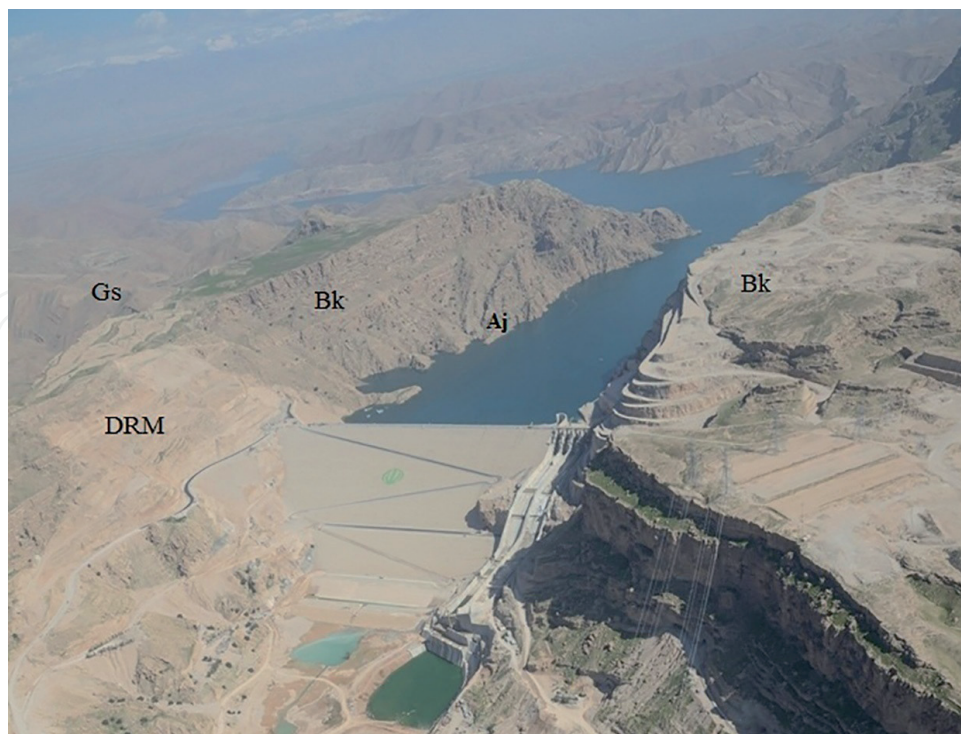


Figure 17. An upstream (eastward) view of Gotvand dam site and the outcropped formations; Bakhtyari (Bk), Agha-Jari (Aj), and Gachsaran (Gs). DRM is displaced rock mass.

Conglomerates of Pliocene Age that displays almost horizontal bedding (**Figure 17**). The Bakhtyari Formation is wholly composed of terrigenous, clastic sediments ranging from silt to conglomeratic boulders. Fractures within this formation are usually vertical and have relatively large openings up to several meters. It is also composed of part of the right abutment as a dislocated and ruptured block (DRM). Along the northern margin of the river, Gachsaran layers are thrust over the Agha-Jari layers by Pir-Ahmad fault (**Figures 18 and 19**). The dam site area is dominated by an anticlinal structure comprising Kuh-e Reshteh and Kuh-e Charkhineha in the north and south of Karun River, respectively [44]. Both of

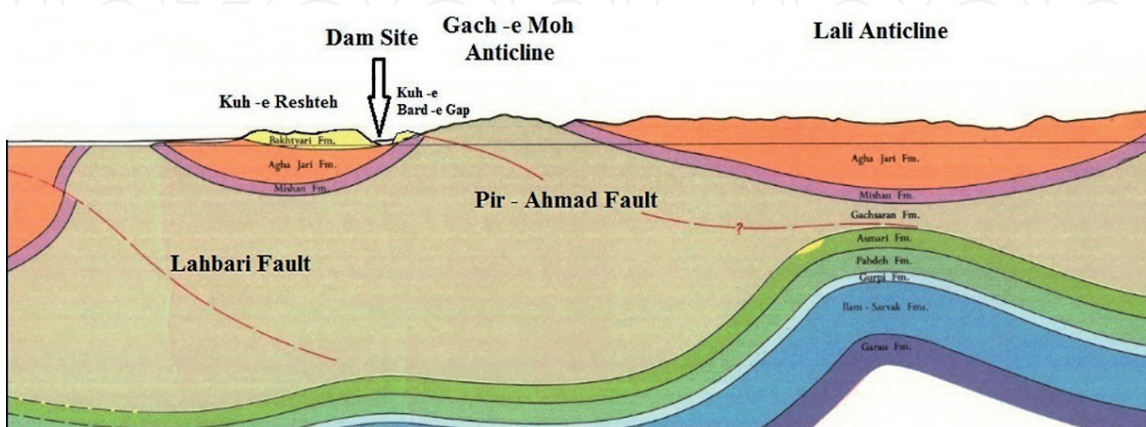


Figure 18. Geological section across the Gotvand dam region.



Figure 19. A close view of Pir-Ahmad Fault in the northern side of Kuh-e Reshteh anticline.

them are composed of Bakhtyari formation. An elongated asymmetrical structure named Gach-e Mun or Gach-e Moh anticline occupies the north side of the dam site in a general NW-SE direction. Its south flank is obscured by the presence of Pir-Ahmad fault [44]. Kuh-e Reshteh is the southern part of the Bakhtyari outcrop on which the dam left abutment is placed. The Lahbari active fault passes along the contact between this outcrop and southern plain (**Figure 18**) and defines the mountain-plain boundary in the Dezful Embayment structural unit [14].

In fact, it forms the northern boundary of the Dezful Embayment (foreland basin of the Neogene molasse of the Agha-Jari-Bakhtyari formations). The river bed is occupied by a small tight anticline composed of Agha-Jari layers with an E-W trend. The anticlinal fold axis is parallel to a fault having the same E-W trend. Agha-Jari formation that composed the dam foundation contains three main joint sets. One set is parallel to the bedding plane. Severe change of joint dips is most probably due to tight folding of the layers and faulting along the river course. The joint surfaces are mostly smooth, polished, and slicken-sided with varying dip angles.

As mentioned above, one of the challenges at Gotvand dam is instability of the dam abutments [42] and its reservoir banks [44]. The dam abutments include considerable volumes of dislocated rock mass of Bakhtyari formation. This is more critical in the right abutment as the rock mass is highly disturbed and deformed (DRM) and apparently illustrates a rock topple (**Figures 17 and 20**). On the other hand, the rock mass in the left abutment shows evidence of a rock slide. The DRM area is specified by extensive development of joints and cracks and its

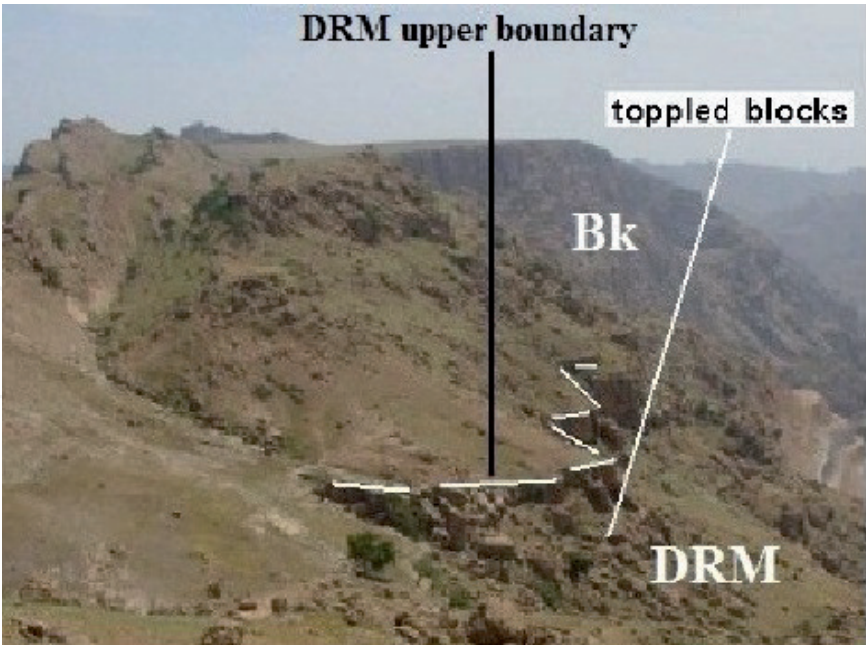


Figure 20. An upstream view of the displaced rock mass (DRM) on the right abutment [42].

extent along the dam axis was estimated between 150 and 200 m [45]. Consequently, water seepage was considered as an extra problem in the right abutment. Lugeon tests in this zone indicated values more than 60 due to the extent of fracturing. The prevailing hydromechanical behavior of the rocks at this abutment was dilatation and washout based on geotechnical investigations [44, 45].

The second problem expected for the Gotvand dam site, is leakage through its foundation via Agha-Jari layers [46]. These layers contain veins of gypsum usually associated with claystone beds. They appear as thin films on the beddings and along joint surfaces with a maximum thickness of 2 cm. The action of Lahbari and Pir-Ahmad thrust faults in the



Figure 21. Simplified geological cross section along the dam axis [44].

south and north of the dam site, respectively, caused severe compression resulted in tight folding of the Agha-Jari layers (**Figure 21**). Subsequently, simultaneous compression of the competent sandstone layers and incompetent siltstone and mudstone layers in the Agha-Jari formation resulted in flexural-slip along the bedding planes, accompanied by shearing and jointing of rocks.

Continual development of forced-folding widens joint apertures that make them favorable for gypsum precipitation. Results of Lugeon test for Agha-Jari rocks at the dam foundation show an average value of 6 up to a maximum of 30 LU. Laboratory experiments estimated the solution rate for the core-drilled gypsum of the dam foundation as 2.49 cm/year. As the number of fractures in gypsum layers increases, solution processes progress. It is calculated that the dissolution of gypsum veins increase the mass equivalent permeability up to 75–300 times depending on aperture width and spacing. The availability of fractures and fissures are primary and main factors for solution progress. In this regard, gypsum veins observed in Agha-Jari formation at the dam foundation could be threats to safety and proper performance of the dam.

7. Conclusions

The knowledge of geological structures gives a reasonable in-sight in to dam construction studies. Site geology and availability of various geologic data obtained from site investigation is a key point in dam construction. It is also clear that the geological nature of different sites is not the same and depends on local and regional geology. Existing experience in dam construction projects shows that geological structure plays an important role in dam site geology and imposes major limitations on dam behavior during and after construction stages. In Karun-1 dam, for example, seepage through two springs downstream the right abutment are related most probably to existing shear zone at that abutment. Besides, rock falling and sliding on the dam abutments due to the downslope dip of bedding is another structure-related problem at the dam site. In Karun-3 dam, almost similar problems are observed but here, the presence of two sub-parallel thrust faults with opposite dip direction resulted in high stresses in the rock that intensified fracturing and subsequent permeability. Variability and complexity of geological structures regarding their tectonic situation result in different scenarios regarding dam's behavior. In this regard, the intersection of longitudinal and transverse faults in the vicinity of Marun dam caused the development of well and highly densified joint systems in the dam abutments that facilitated karstification. This in turn increased permeability of the rocks that was followed by extensive seepage during the dam construction. The role of geologic structure on geotechnical properties of dam sites is clearly seen in cases such as Gotvand Dam. Here, high fracturing and instability in the right abutment caused costly treatments including various stabilizing works such as grouting, geomembrane, and shotcrete. Finally, all the abovementioned examples indicate the impact of geological structure on various procedures either during constructing a dam or after its completion and close relation between structural geology and rock behavior.

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