

Geotechnical characteristics of Bakhtiary dam site, SW Iran: the highest double-curvature dam in the world

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Abstract The Bakhtiary Hydropower Project with a 325 m high dam will be constructed on Bakhtiary River, in southwest Iran. The main dam has been designed as a double-curvature concrete structure which will be the highest one of its type in the world. Geologically, the dam site is located on siliceous limestone of the Sarvak Formation in the northwestern part of the folded Zagros. A large number of complicated geological structures in the study area, such as folding and duplex structure, faults, chevron folds, kink band zones as well as joint and fracture systems, raised concerns regarding the acceptability of the site for such a monumental dam. To create a comprehensive geotechnical model of the dam site and appurtenant structures, very extensive surface and subsurface investigations were carried out, including core drilling, water pressure testing, driving exploratory galleries for engineering geological mapping, a rock mass discontinuity survey and in situ rock mechanical tests. This research applies the results of the engineering geological and geotechnical investigations to define the geomechanical model of the dam site enabling options to be considered to achieve a safe dam design. The investigations show the rock mass of the dam site area is intersected by four main discontinuities namely, the bedding plane(s) of the rock mass and three major joint sets. Water pressure tests provide data about the permeability of the rock mass which is significantly dependant on the joint properties and the geological

structures. These parameters, set the criteria for the design of the grout curtain at the dam foundation. The rock mass classification of the dam site was determined mainly based on the gallery survey and core logging using the rock mass rating, geological strength index (GSI) and Q system. Six classes of rock mass qualities were distinguished which show a fair to good rock mass at the dam foundation. From the plate load test results, a site-specific correlation was developed for estimating the modulus of deformation of the rock masses using GSI value. The estimated engineering geological and geotechnical parameters at the dam site are generally favorable and suitable for the safe design of the Bakhtiary arch dam with a height of 325 m.

Keywords Bakhtiary dam · Sarvak Formation · Geotechnical investigation · Geomechanical model · Rock mass classification · Plate load test · Rock mass deformability

Introduction

Catastrophic dam failure usually results in sudden flash which inevitably leads to huge loss of lives and destruction of the environment; for example, the 1963 overtopping of the Vajont dam in Italy caused 2,600 deaths, the 1976 failure of the Teton dam in the USA caused a hundred deaths and economic loss of about 1 billion dollars and the 1993 failure of the Gouhou dam in China, caused 300 deaths (Luo et al. 2012). Suitable information on the geological condition, geotechnical parameters and hydrogeological situations of dam site is vital to design and guarantee the safety of dam body. The role of geotechnical investigation becomes even more important as the dimensions of such structures are increased in height, depth and

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volume of reservoir. Referring to the published reports, it is clear that some well-known dams failed due to inadequate, pre-construction geological and geotechnical investigations. For instance:

- the St. Francis concrete gravity arch dam failed due to the partial reactivation of an ancient bedrock landslide which comprised the dam's entire left abutment (Rogers 2006).
- the Malpasset double-curvature concrete dam collapsed due to the existence of a low shear strength zone in the left abutment associated with excessive uplift pressure caused from the water flow passing through permeable discontinuities (Londe 1987; Serafim 1987).
- an overtopping occurred at the Vajont double arch dam when a huge landslide of a total volume of 270–300 million m³ of rocks and debris invaded into the reservoir. The slide occurred on a thin layer of high plasticity clay (Hendron and Patton 1987) or on a normal fault plane (Mantovani and Vita-Finzi 2003) or on a very thick shear zone (40–50 m) located at the bottom of the prehistoric landslide (Paronuzzi and Bolla 2012).
- the Teton earth fill dam was located on fissured rhyolite which allowed seeping the water through the dam and led to internal erosion and eventually dam failure (Seed and Duncan 1987).
- the Austin dam was constructed on porous sedimentary rock with a low shear strength zone at the dam foundation which caused the dam to fail (Serafim 1987; Reddy 1995).

Since then, several systematic methods and mandatory requirements have been developed to enable characterization of the geotechnical properties of dam sites. Currently, the analysis of such parameters has not only become fast but also highly accurate using modern geotechnical investigative techniques.

With regard to the Bakhtiary Dam and Hydropower Project (the subject study), the main dam body was designed as a double-curvature concrete arch type with the maximum height of 325 m and crest length of 509 m. This is the highest arch dam in the world. The dimension of the dam, the complicated geological conditions of the site and the specific risks associated with the failure of the Bakhtiary dam complex (e.g., the destruction of the railway line, a possible failure of the 203 m high Dez arch dam and the likely consequential flooding of several cities in Khuzestan Province such as Dezful, Andimeshk and Ahwaz) necessitated a detailed geotechnical investigation. The results from this investigation were carefully analyzed and cautiously interpreted prior to the final dam design.

In order to investigate the site potential for constructing a huge dam like the Bakhtiary dam, detailed and extensive

surface and subsurface explorations were carried out (BJVC 2009a). These investigations comprised:

- Twelve exploratory galleries were excavated in different elevations with the total length of 3,436 m,
- Three hundred and four boreholes were drilled with the total length of about 17,040 m.

Due to the steep cliffs and locally even overhanging walls at the dam site, several hundred meters of sidewalks in a zigzag shape were built into the walls as access roads to the exploratory work locations. These pedestrian sidewalks are mostly constructed using anchors installed into the rock (with a depth of almost 0.8 m and with approximately 1 m spacing), putting ladders or wire mesh on them, placing gravel on the wire mesh and then concreting them. These paths are 0.25–0.5 m wide. The installation of anchors has not only made it possible to ply on them but also has increased safety of passage. Mechanical equipment and machinery such as drill rigs and rock mechanics test equipment were hauled using helicopters.

This paper presents the outcomes from these investigations which were used to define the geomechanical model of the dam site. These parameters comprised rock mass quality, permeability, discontinuity surveys, rock mass classification and the deformability of the rock mass. Generally, the results show that the geological and geotechnical conditions of the rock mass underneath the dam structures are suitable for the construction of an extraordinary dam with a height of 325 m.

Background information

Project description

The Bakhtiary Dam and Hydropower Project are located on Bakhtiary River (the main tributary of the Dez River), in Lorestan Province about 100 km south of Khorram Abad and 70 km northeast of Andimeshk, southwest of Iran (Fig. 1). The dam body was designed with maximum height of 325 m and crest length of 509 m at elevation of 840 m asl, so it will be the highest double-curvature concrete arch dam in the world.

This project was planned to be a multipurpose development with the primary function of electricity generation, increasing the volume of regulated water in the Dez catchment, decreasing the amount of sediment in the Dez dam reservoir as well as the associated benefits of flood control (BJVC 2009b).

The total storage capacity of the reservoir was estimated to be about 4800MCM at normal water level of 830 m asl, and the reservoir live storage to be about 2122MCM for the minimum operation level of 785 m asl (BJVC 2009b).

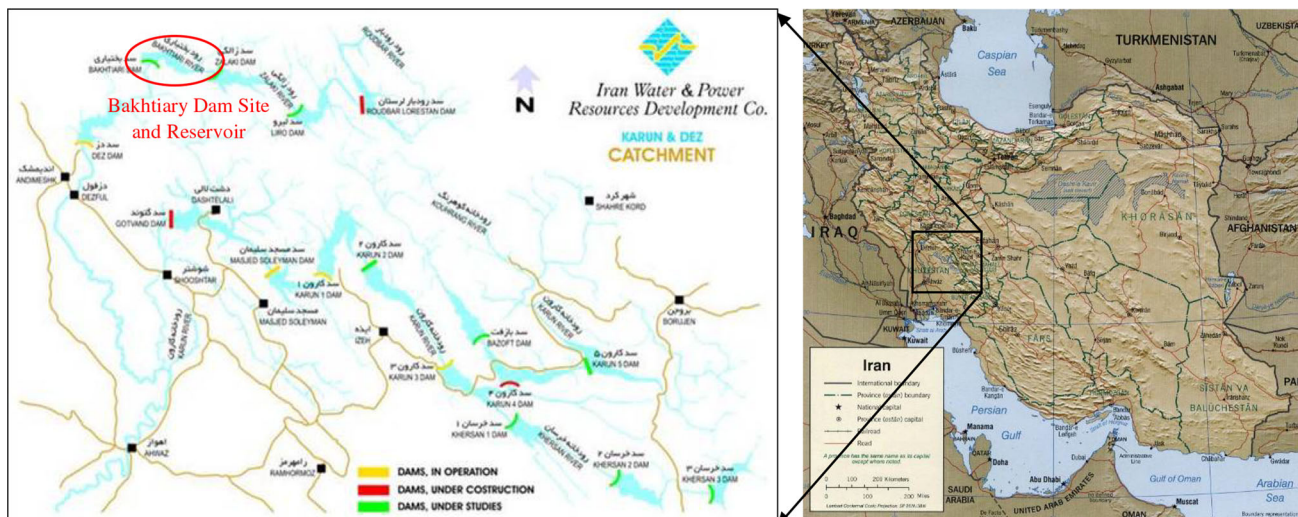


Fig. 1 Location of the Bakhtiary Dam and Hydropower Project area on map of Iran and a close view of the dam site on the Karun-Dez catchment area map

The hydropower plant was designed as an underground powerhouse complex with 6×250 MW units with a total installed capacity of 1,500 MW. The six Francis turbines working at a nominal head of 270 m are expected to produce an annual energy output of about 3,000 GWH (BJVC 2009b).

Dam site geology

The Bakhtiary dam site and its reservoir are located in the northwestern part of the folded Zagros, at the boundary of Lorestan and Dezful embayment zones. The folded Zagros is a part of Zagros tectono-sedimentary province which is limited by thrusts Zagros in the northeast and to the Khuzestan plain in the southwest. The thick sediments of this zone deposited from the Triassic through the Pliocene Era and were subsequently folded and deformed during the Plio-Pleistocene by the last Alpine orogenic phase (Motiei 1993). This tectonism generated sets of anticlines and synclines which are characterized by mostly vertical axial planes associated with many thrust faults in Zagros area. The structures generally trend NW-SE.

The siliceous limestone of the Sarvak Formation forms the most important rock of the Bakhtiary dam site and its reservoir. This formation belongs to the Bangestan Group in age of Middle Cretaceous Period. Based on the thickness of bedding planes and the existence of siliceous components, this formation was locally divided into seven units from Sv1 to Sv7 by the Bakhtiary Joint Venture Consultants (BJVC); the properties of rock units are presented in Table 1 (BJVC 2009a). A generalized geological map of the dam site including of geological units, dam body, diversion tunnels and spillways is presented in Fig. 2, and a cross section along the dam axis (Section A-A') is shown in Fig. 3. As can be seen, whilst unit Sv1 does not outcrop at the dam site, it forms

Table 1 Description of the rock units at the Bakhtiary dam site

Rock units	Description
Sv1	Medium to thickly interbedded dark gray marly limestone with black laminated marlstone to shale
Sv2	Thinly to medium bedded dark gray limestone to marly limestone with thin black laminated marlstone to shale interbeds
Sv3	Thinly to medium thick interbedded dark gray marly limestone and siliceous limestone
Sv4	Medium to thickly bedded dark gray limestone with small siliceous nodules
Sv5	Thickly to very thickly bedded dark gray limestone with big siliceous nodules
Sv6	Medium to thickly bedded dark gray limestone and marly limestone with thin interbeds of marlstone
Sv7	Thinly to medium bedded dark gray limestone and marly limestone with thin shale interbeds

the core of the Siah Kuh anticline. The dam body is situated in an area mainly underlain by units Sv2-Sv4 (Fig. 3). Unit Sv2 is exposed in the valley bottom and at the lowest level of the dam abutments. Units Sv3 and Sv4 are located in the middle and at the highest level of the abutments, respectively (Fig. 3). Diversion tunnels will pass through units Sv2-Sv7, and the underground powerhouse complex will be excavated in units Sv5 and Sv6.

Tectonic evaluation and structural features

Several key features of the geological structure of the dam site needed to be considered in the dam design; such as the folded and duplex structure of the Giriveh-Siah Kuh

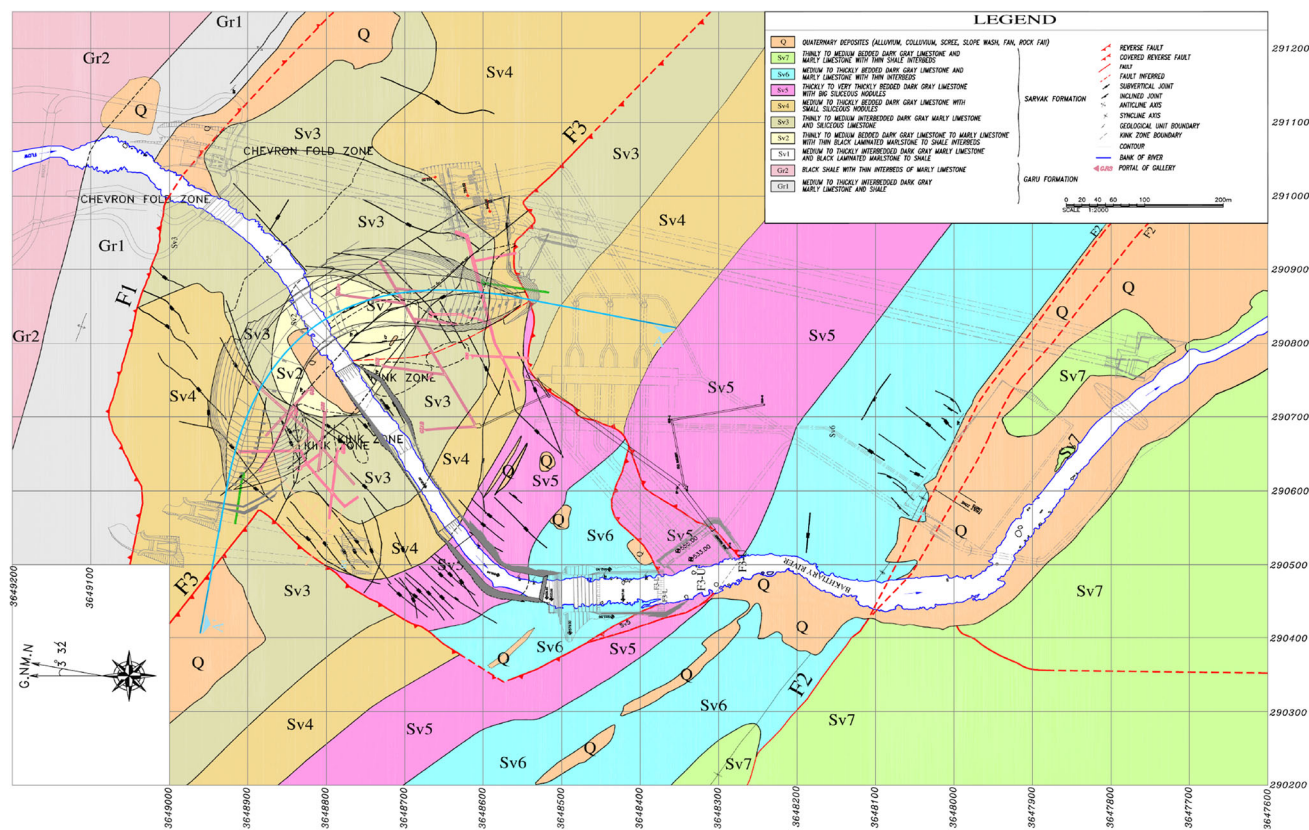


Fig. 2 Geological map of the Bakhtiary Dam and Hydropower Project, Sv1 has no outcropped in the dam site and Sv2 to Sv4 are placed in the dam foundations

duplex-anticline, the fault complex (the F1–F3 fault system and F2 fault), chevron folds and kink band zones as well as the joint systems (Figs. 4, 5).

Evaluation of the tectonic history implies that the Giriveh-Siah Kuh duplex-anticline and F1–F3 fault system are first-order structures, whereas the chevron folds, kink bands and joint sets are the second- and third-order structures.

Along the F1–F3 fault system, the sedimentary sequence of the Giriveh anticline was thrust over the corresponding sequence of the Siah Kuh anticline (Fig. 4). The chevron fold zones with tight hinges (amplitudes of 5–10 m) are related to the strain induced by the thrusting of the Giriveh anticline over the Siah Kuh anticline along the F1–F3 fault system (Figs. 5, 6a). Changes in dip and thickness of the limestone layers associated with the tectonic pressure led to the shortening of rock mass in the brittle condition and created the kink band zone. The disturbed kink band zones with typically narrow hinges (amplitudes of 1–3 m) are close to the core of the Siah Kuh anticline which probably developed along the weakness zones during the folding as a result of accommodation problems (Figs. 5, 6b). It seems that the stress which created the chevron fold zones was much higher and more

homogenous (thrusting along F1) than the stress that created the kink. Finally, the appearance of the long J1 major joints is related to a very late dome-like uplift of the anticline structure in the dam site area under brittle conditions.

Site investigation and rock mass properties

Discontinuities

Based on the detailed joint survey in the six exploratory galleries GR1 to GR3 (located on the right bank) and GL1 to GL3 (located on the left bank), the rock mass fabric at the dam site area comprises four discontinuities including bedding planes and three major joint sets; J1, J2 and J3.

Figure 7 shows the stereographic projection of the bedding planes of both limbs of the Siah Kuh anticline which is the predominant structure. The dip angle of the southwestern limb is 75° toward SW (215°), whereas the dip of the northeastern limb is 50° toward NE (030°).

The scatter of the bedding planes represents the data pertinent to deformed kink band zones in units Sv2 and Sv3. The poles of these bedding planes plot on a great

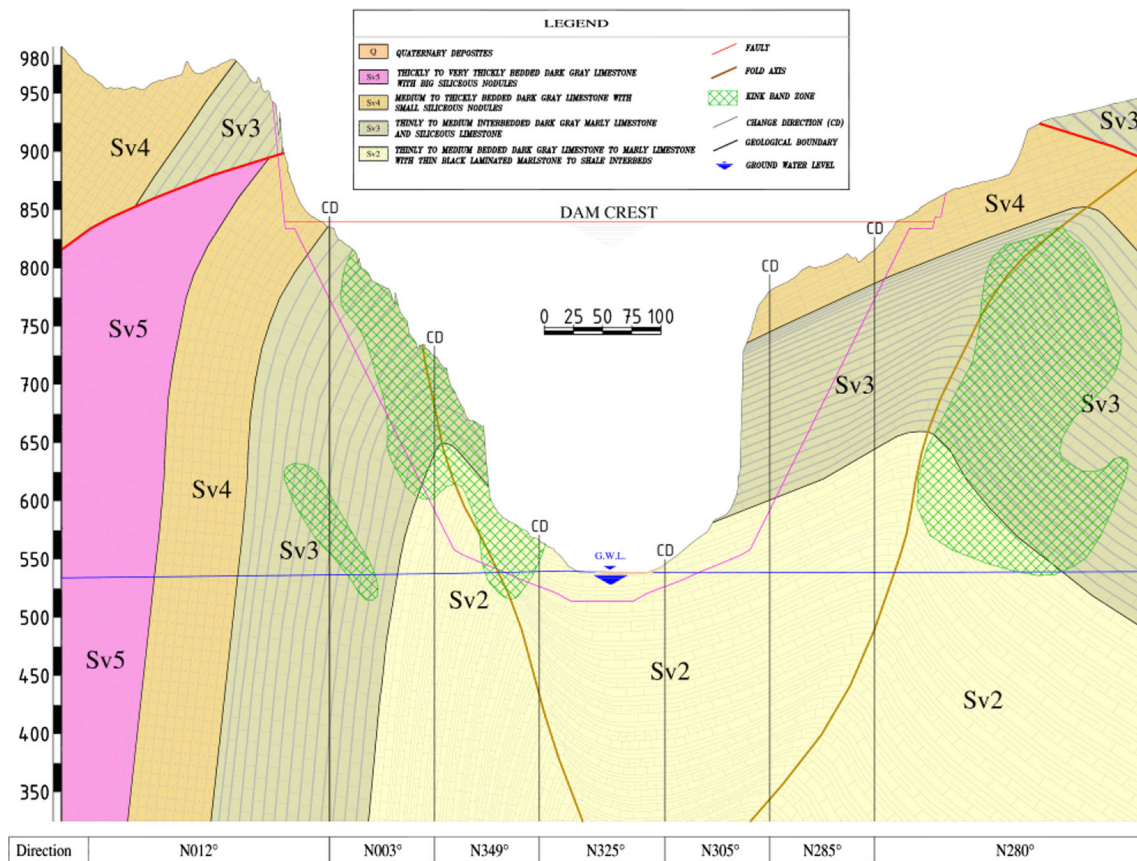


Fig. 3 Developed geological section along the dam axis and geological units of Sarvak Formation in abutments (Section line is shown on the geological map of dam site as section A–A')

Fig. 4 Giriveh anticline thrust over the Siah Kuh anticline along the F1–F3 fault system and created a duplex structure, view to the right abutment



circle showing the plane normal to the fold axis of Siah Kuh anticline; FA 305°/05° (see Fig. 7).

Joint set J1 is the most frequent and important joint at the dam site which is recognized as the main factor creating the step-like erosion/morphology of the walls of the

gorge. This joint set is in cluster form with a persistence of several meters up to a few tens of meters. Figure 8a, b shows the stereographic projection of the major joint set J1 which is divided into two subsets, namely; J1A (310°/70°), a steeply inclined set representing the larger of the joint

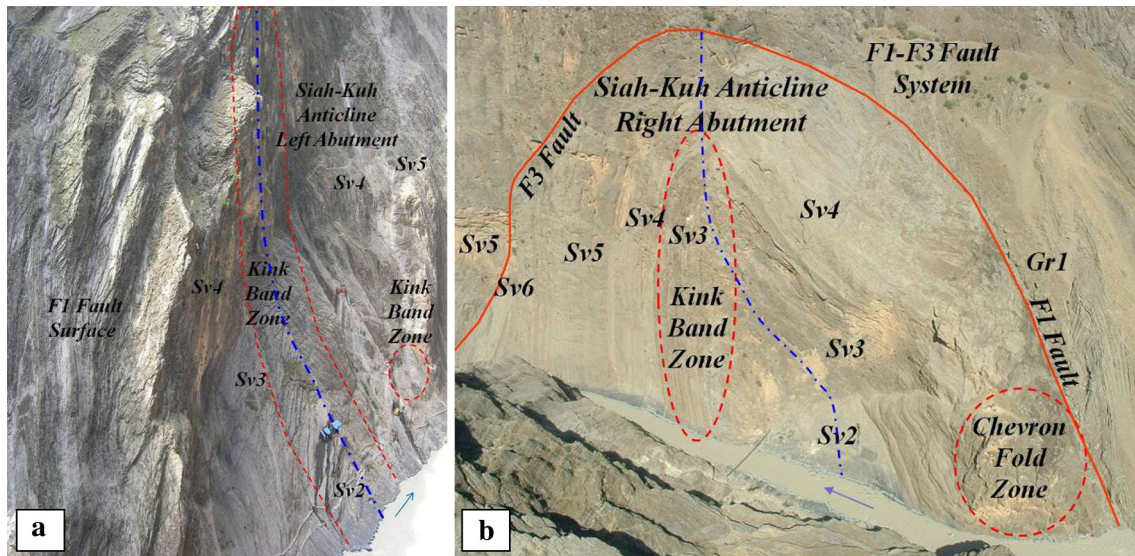


Fig. 5 General view of the geological condition at the dam abutments in the core of Siah Kuh anticline, main geological rock units (Sv2 to Sv6) and structural geology features such as anticline

axis, kink band zones, chevron fold zones, F1–F3 fault system are shown (**a** left abutment and **b** right abutment)

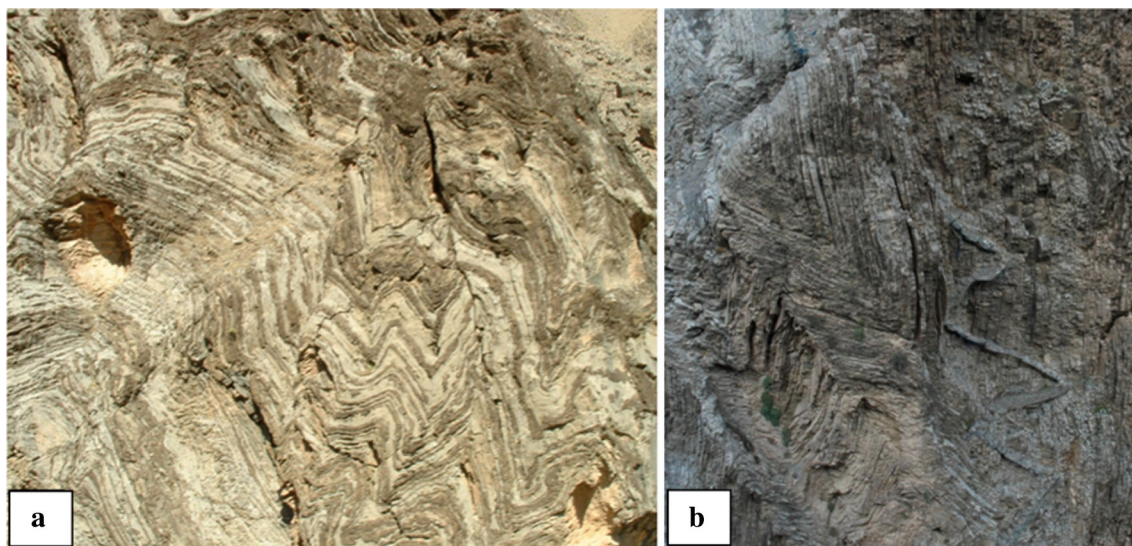


Fig. 6 **a** Chevron fold zone next to the F1 fault and **b** kink band zone in the core of the Siah Kuh anticline (location of these structures are addressed in the left and right abutments in Fig. 5)

sets observed around the study area particularly on the surface, and J1B ($310^{\circ}/40^{\circ}$), a less inclined set, generally observed inside the galleries. The second joint set (J2), is less frequent and is divided into a main (J2A; $125^{\circ}/35^{\circ}$) and a subordinate (J2B; $125^{\circ}/75^{\circ}$) subset (Fig. 8c). Persistence of J2 joint subsets varies from some decimeters to few meters. The J1 and J2 joint sets developed more or less parallel to the ac-plane and their pole normals coincide with the b-axis of the fabric (Sander 1948). The joint set J3

($045^{\circ}/15^{\circ}$), has the least frequency and is not observed in all locations (Fig. 8d).

Table 2 shows quantitative descriptions and statistical distributions of discontinuities at the site according to ISRM (1981).

The distribution of these joint sets is not uniform and varies from downstream to upstream and from level to level of the galleries. Table 3 presents the non-uniform distribution of the joint sets at the Bakhtiary dam site.

Fig. 7 Stereographic projection of bedding planes in the dam site area, northeastern limb (030°/50°), southwestern limb (215°/75°) and fold axis (305°/05°)

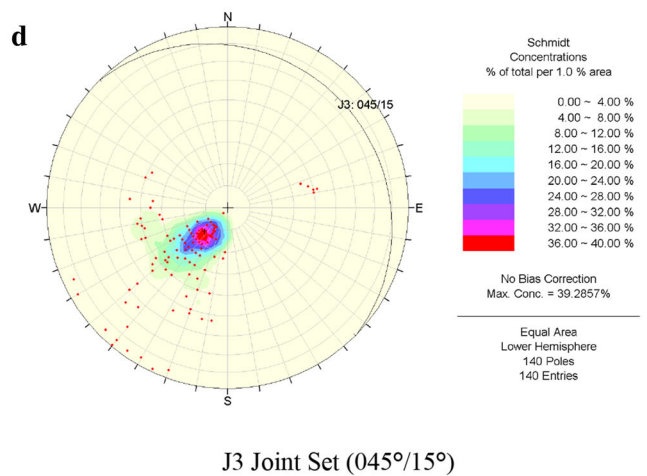
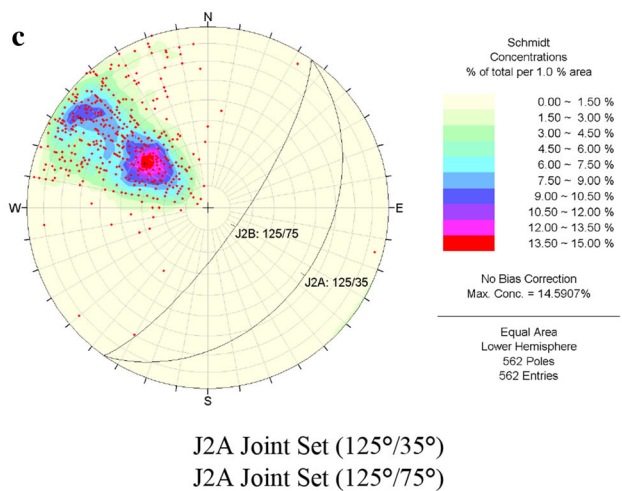
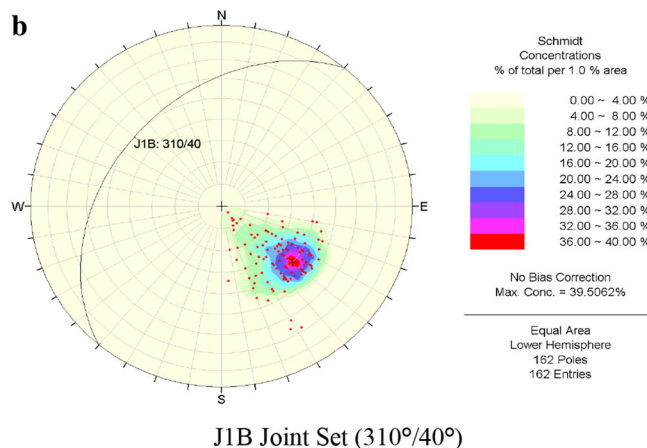
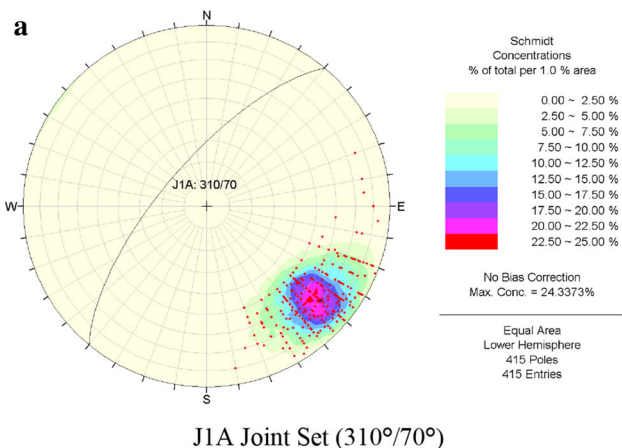
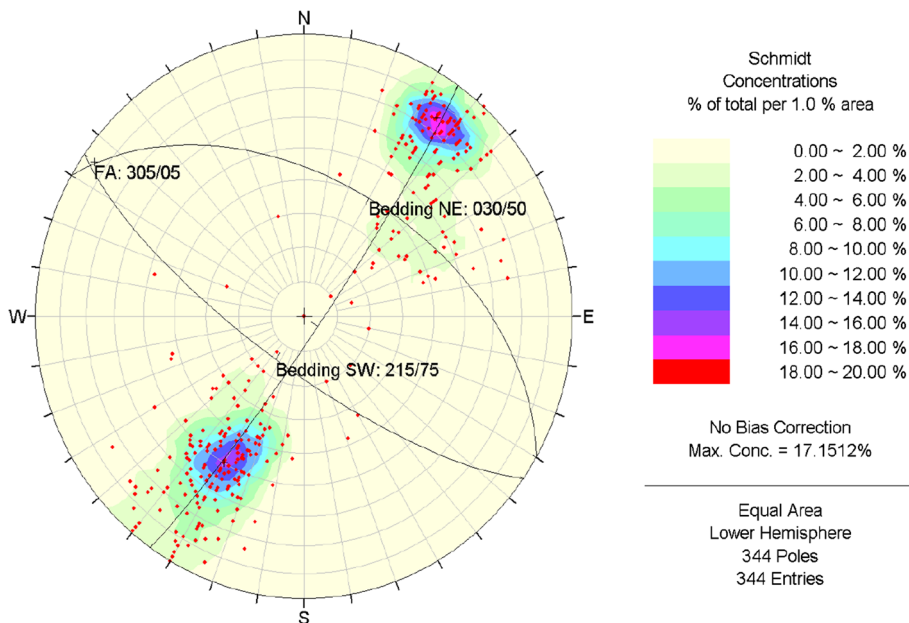


Fig. 8 Stereographic projection of joint sets at the Bakhtiary dam site

Table 2 Quantitative description and statistical distributions of discontinuities at the Bakhtiary dam site

Characteristics	Value/description	Distribution (%)			
		Bedding	Join set J1	Join set J2	Join set J3
Aperture (mm)	0.1–1	90.0	90.0	95.0	95.0
	1–5	10.0	10.0	5.0	5.0
Spacing (cm)	2–6	1.5	2.5	3.0	6.0
	6–20	47.0	48.5	52.0	25.0
	20–60	44.5	45.0	43.5	62.5
	60–200	3.5	4.0	1.5	6.5
	200–600	3.5	0.0	0.0	0.0
Infilling	Clay	42.5	10.0	2.0	0.0
	Calcite	46.0	67.5	55.0	43.0
	Bitumen	4.5	1.0	0.0	0.0
	FeO	2.0	0.0	0.0	0.0
	Tight	5.0	21.5	43.0	57.0
Roughness	Undulating—slickenside	19.0	2.0	0.0	0.0
	Planar—slickenside	41.0	2.0	1.0	0.0
	Undulating—smooth	5.0	1.0	1.0	0.0
	Planar—smooth	18.0	47.0	54.5	72.5
	Undulating—rough	1.0	0.0	0.0	0.0
	Planar—rough	16.0	48.0	43.5	27.5

Table 3 Distribution of the main joint sets at the dam site

Gallery name	Joint set no.	Elevation (m asl)	Downstream side (left/right)	Upstream side (left/right)
GL/GR3	J1A	GR3 # 754 GL3 # 780	Dominant/present	Dominant
	J1B		Rare	Dominant
	J2A		Dominant	Present
	J2B		Rare	Present
	J3		Rare/dominant	Rare
GL/GR2	J1A	695	Dominant/present	Present
	J1B		Present/dominant	Rare
	J2A		Present	Present
	J2B		Rare	Present/dominant
	J3		Absent/rare	Dominant/rare
GL/GR1	J1A	557	Dominant	Dominant/rare
	J1B		Present	Present
	J2A		Rare/present	Rare
	J2B		Present/rare	Dominant
	J3		Absent	Rare

Rock quality designation

In geotechnical terms, one of the simplest and easiest methods to describe the quality of the rock mass is by means of the degree of fracturing in drill cores (Sen 1990). Rock quality designation (RQD) was proposed by Deere (1963) which is the percentage of total intact lengths that are longer than a specific threshold value of 10 cm. On the

basis of RQD value, the rock can be classified as excellent (>90 %), good (75–90 %), fair (50–75 %), poor (25–50 %) and very poor (0–25 %).

The average value of RQD and its frequency distribution for each class were calculated separately according to the dam body position (right and left abutments, river bed and powerhouse area) and for the litho-stratigraphic units (Sv1 to Sv7), as presented in Fig. 9. The histograms show the

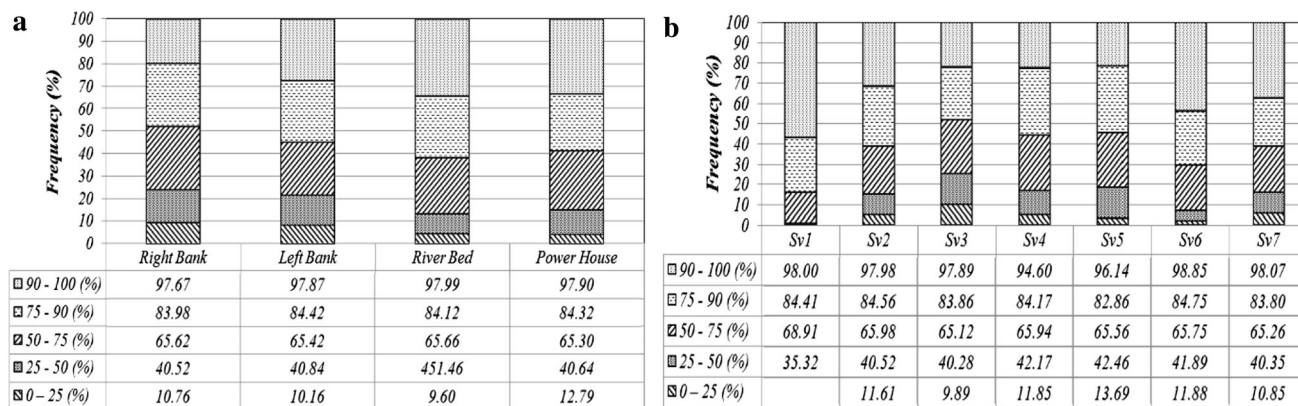


Fig. 9 Histograms showing the frequency of the RQD classes (based on the classification of Deere 1963) at the Bakhtyary dam site regarding to **a** locations and **b** rock units; in the tables below the graphs, average RQD values in each class are presented

frequency of the RQD, and the tables below them present the average value of RQD in each class.

Most of the RQD values in all locations at the dam site, are more than 75 % which indicates good and excellent rock mass conditions (Fig. 9a). More than 85 % of the cores in units Sv2 and Sv4 in the dam foundation and abutments were classified as fair, good and excellent rock mass quality. The intensity of the rock mass deformation within the kink band zones especially in unit Sv3 decreases the RQD value in this unit. The very poor and poor rock mass classification occurs least reflecting the existence of a good rock mass quality at the dam site (Fig. 9b).

Rock mass permeability

During borehole drilling, water pressure tests (WPTs) were carried out and the permeability of the rocks was calculated in terms of Lugeon values. A total of 1,904 WPTs were evaluated based on Houlbys method (Houlbys 1990) to investigate the permeability of the dam site. Average Lugeon values and relevant frequencies were determined for different locations (right and left abutments, river bed and powerhouse area) and litho-stratigraphic units (Sv1 to Sv7), as presented in Fig. 10. The histograms show the frequency of the Lugeon values, and the tables below them present the average Lugeon value in each class.

According to the WPT results, the permeability of the rock mass is bi-modally distributed (Fig. 10a). About 32 % of tests show high permeability (15–50 Lu), whilst 18 % of the tests show very low permeability (1–5 Lu); the lowest frequency corresponds to the range of medium permeability (10–15 Lu).

Generally, the permeability of the units Sv1 and Sv2 is low; about 58 and 47 % of Lugeon values are <10 Lu which is attributed to the existence of interbedded shale layers in these units (Fig. 10b). The permeability of the unit Sv3 is high to very high, and about 58 % of Lugeon

values are more than 15 Lu which indicated testing in the fractured area of disturbed kink band zones. Permeability of the unit Sv4 is high and very high (about 70 % of Lugeon values are more than 15 Lu) as a result of a degree of dissolution along the joints in the upper elevations. Permeability of the other rock units (Sv5, Sv6 and Sv7) is very low and low, and some permeability anomalies are due to the existence of the local open joints.

Comparison of the Lugeon and RQD values shows the high Lu values correlating with the high RQD values which indicates the potential for a singular water flow pathway (a fracture zone or a large open joint) in increasing the permeability of the impervious rock mass. Furthermore, the scatter of the Lugeon values can be attributed to the rock mass disturbance within the kink band zones which shows higher permeability compared to less deformed areas.

The development of karstic features was investigated to determine their effect on the rock mass permeability. As aforementioned, Sarvak Formation components are not pure limestone but include some siliceous, organic nodules and bands and impure marls (BJVC 2009a). Thus, it is impossible to observe developed karstic features at the dam site. That said, field observations showed no karstic features (vugs, caves and siphons). This finding was backed up by the geotechnical investigations (i.e., no rod fall in more than 17,000 m of borehole drilling and no cavities found in more than 3,400 m of exploratory gallery). It was therefore concluded that no superficial and/or deep karstic features are present at Bakhtyary dam site.

Rock mass classification

Rock units of the Sarvak Formation at the dam site were classified using rock mass rating (RMR) RMR₈₉ (Bieniawski 1989), geological strength index (GSI) (Marinos and Hoek 2000) and *Q* (Barton 2002) systems. Furthermore, the deformed rock masses in the kink band zones were

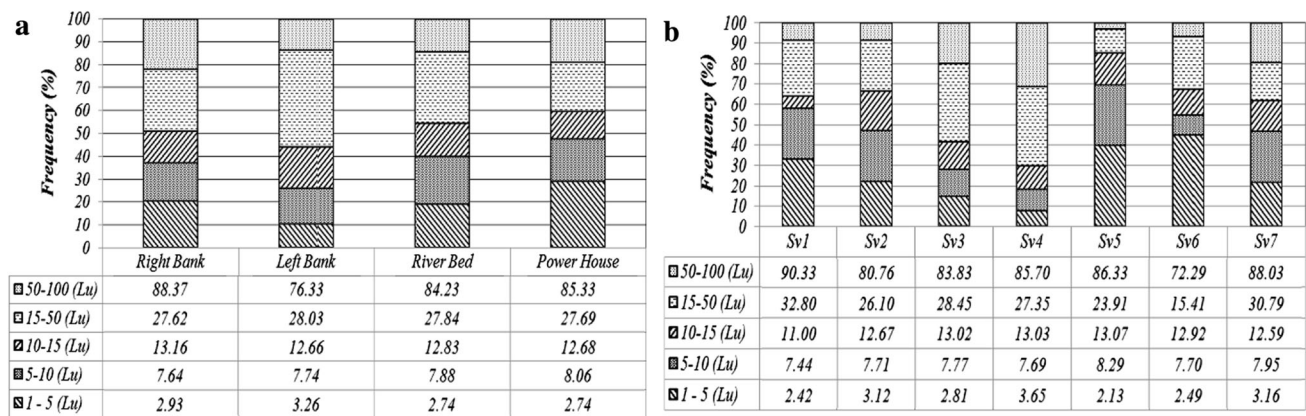


Fig. 10 Histograms showing the frequency of the Lugeon values (based on the classification of Houlsby 1990) at the Bakhtiary dam site regarding to **a** locations and **b** rock units; in the tables below the graphs, average Lugeon values in each class are presented

Table 4 Rock mass classification at the Bakhtiary dam site based on RMR_{89} (Bieniawski 1989), GSI (Marinos and Hoek 2000) and Q (Barton 2002) systems

Rock units	RMR_{89}	Q_{Min}	Q_{Max}	Q_{Mean}	Q_{MF}	GSI	E_{rm} (GSI) (GPa)
Sv2 + Sv3 (disturbed, Type A)	30–51	0.002	80	0.46	0.19	35–50	4.15
Sv2 + Sv3 (disturbed, Type B)	44–55	0.002	90	1.00	1.50	45–50	6.38
Sv2 + Sv3 + Sv4	48–66	0.002	100	1.25	2.69	45–60	9.69
Sv5 + Sv6 (disturbed)	41–72	0.01	100	0.91	1.47	45–65	12.34
Sv5 + Sv6	58–59	0.002	150	7.26	5.23	55–65	18.12
Sv7	46–56	0.002	100	2.8	1.00	45–55	8.21

Estimated deformability of rock masses using the empirical formula suggested by Hoek and Diederichs (2006) when disturbance (D) is close to 0.05

considered as independent units and classified separately, i.e., Sv2-disturbed, Sv3-disturbed and Sv5 and Sv6-disturbed. RMR and GSI values were separately measured in the exploratory galleries, and Q values were calculated in the boreholes.

Table 4 shows the rock mass classification applied to the rock units of the Sarvak Formation. Units with similar rock mass properties were grouped into range classes; this approach enabled essentially disparate rock units to be considered on the basis of their geotechnical properties, as follows:

- Sv2 and Sv3-disturbed, Type A
- Sv2 and Sv3-disturbed, Type B
- Sv2, Sv3 and Sv4
- Sv5 and Sv6-disturbed
- Sv5 and Sv6
- Sv7

Values of the RMR, Q and GSI classification systems corresponding to the above rock classes are shown in Table 4; Q values are presented in the forms of the Q values minimum (Q_{Min}), maximum (Q_{Max}), mean (Q_{Mean}) and most frequent (Q_{MF}).

The RMR, Q and GSI values were compared using the suggested equations by Barton 1995 (Eq. 1) and Hoek 2007 (Eq. 2). In Eq. (1), Q values in the term of mean (Q_{Mean}) and most frequent (Q_{MF}) served to estimate the RMR.

$$RMR = 15 \times \log_{10}(Q) + 50 \quad (1)$$

$$GSI = RMR'_{89} - 5 \quad (2)$$

From the good agreement between the directly measured GSI and calculated one, the ranges of the suggested GSI values for the abovementioned rock mass classes were defined, as shown in Fig. 11.

Modulus of deformation

To estimate the rock mass deformation modulus, a large number of in situ rock mechanics tests were carried out at Bakhtiary dam site; these included plate loading, large flat jack and dilatometer tests. The investigations showed that plate load tests (PLT) provided the most reliable results on the measurement of rock mass deformability.

The plate load tests were carried out in the galleries with a nominal cross-section size of about 2 m × 2 m based on

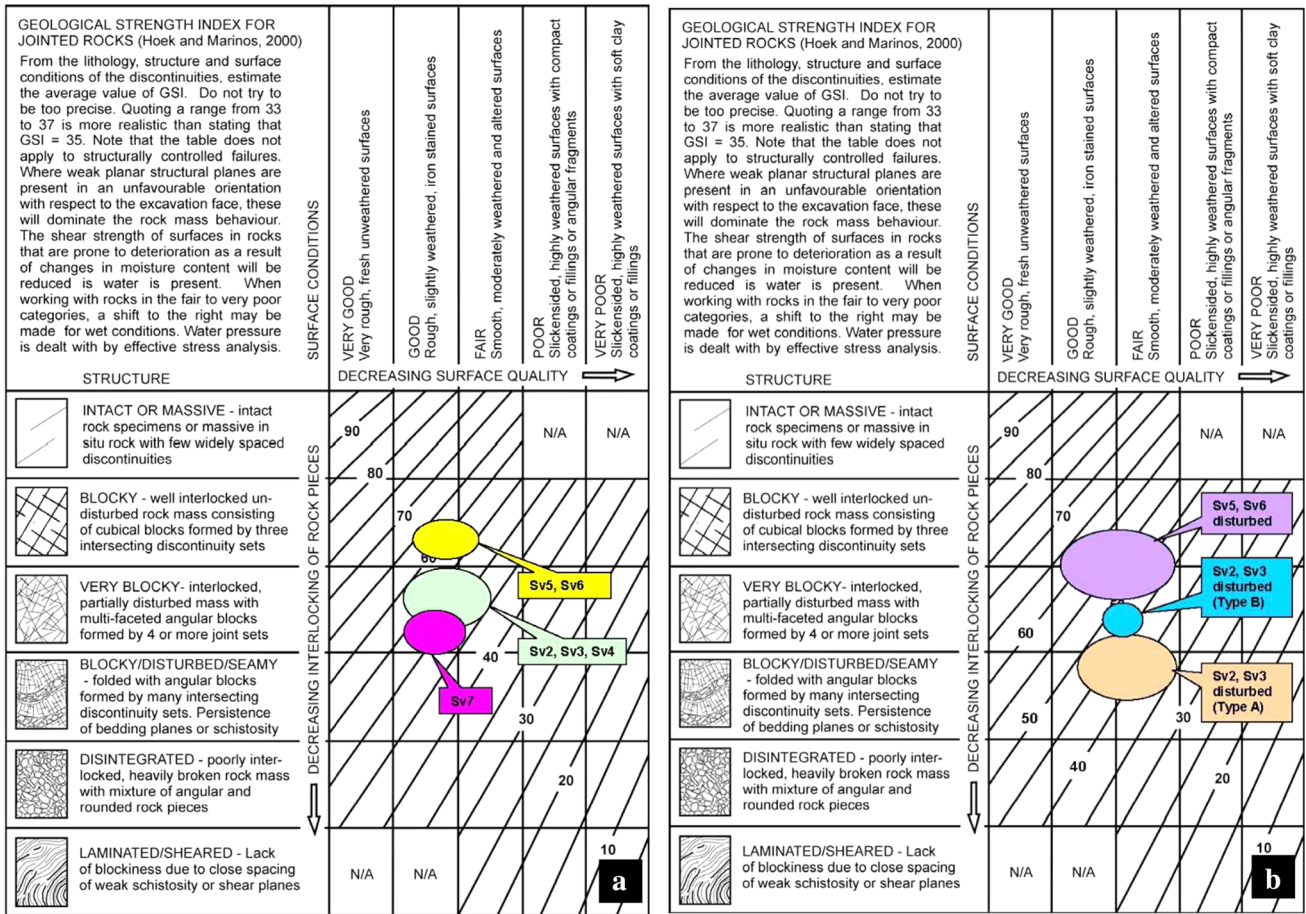


Fig. 11 Range of estimated GSI values for the different rock mass classes at the Bakhtiary dam site in **a** undisturbed condition and **b** disturbed condition

the ISRM suggested method for determination of the rock mass deformability (ISRM 1978). Each test was carried out in five loading–unloading cycles under various loads up to maximum load of 20 MPa (plate diameter of 915 mm) and 40 MPa (plate diameter of 650 mm). To characterize the deformability of the rock mass under constant load, at the peak of each loading cycle, stress was kept constant. Each test includes two opposing loading plates with five point borehole extensometers inside the central borehole underneath each plate (Fig. 12a). Measurements were taken at 1 min time intervals.

Peak to peak modulus of deformation (D_{pp}) is shown on a typical pressure–displacement curve in Fig. 12b. D_{pp} reflects both elastic and inelastic behavior of the tested rock mass between the 1st and 4th cycles.

Calculation of the rock mass modulus of deformation (E_{rm}) was carried out based on the proposed method by Unal (1997). According to the Unal’s method, for the rigid plate load testing, the main formula is expressed as:

$$E_{rm} = \frac{q_{av} \times a}{2w_{z,0}} \left[2(1 - \nu^2) \text{arc cot } \frac{anz}{z^2 + 1} + (1 + \nu) \frac{z}{z^2 + 1} \right] \quad (3)$$

where, “ q_{av} ” is average stress on the loaded surface (MPa), “ a ” is radius of the loaded circular area (m), “ $w_{z,0}$ ” is displacement in the direction of the applied load beneath the center of circle (at the depth = 0) in mm, “ ν ” is Poisson’s ratio and “ z ” is depth from the surface (m).

Results of the 48 plate load tests with maximum pressure of 20 MPa were used to estimate the deformability of rock masses at Bakhtiary dam site. For this reason, a correlation was developed between the overall modulus of deformation (E_{rm}) of the rock mass which correspond to the D_{pp} value obtained from PLTs, and the results of their GSI values estimated based on the suggested approach by Marinos and Hoek (2000). The GSI values of the rock mass surface at the vicinity of plate load testing area were estimated from the diagrams

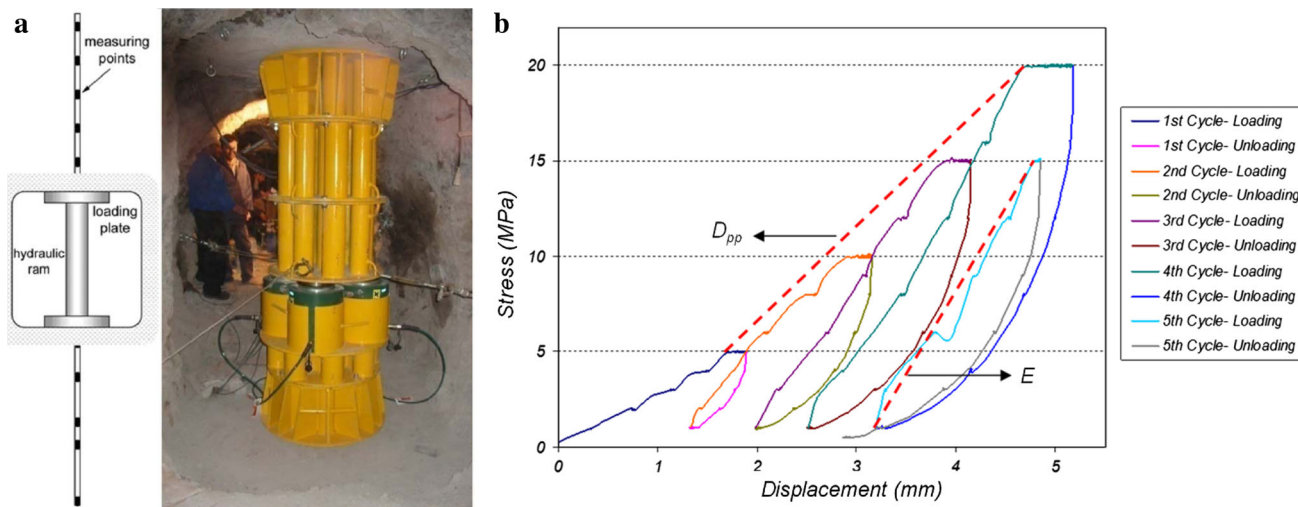


Fig. 12 a Plate load test setup at Bakhtiary dam site and b a typical Pressure–Displacement curve in plate load testing and definitions of peak to peak modulus of deformation (D_{pp}) and modulus of elasticity (E) for the rock mass

proposed Marinou and Hoek (2000) and compared to the calculated GSI from the RMR and Q classifications on the cores of the central holes using Eqs. (1) and (2). A good agreement between the directly measured GSI values and calculated ones from RMR and Q classifications was found. Consequently, the GSI values obtained from the classification of rock mass at the surface and in the central holes were used to develop a correlation with the overall modulus of deformation (E_{rm}).

Figure 13 shows the result of this correlation associated with the family curves based on the empirical formula

suggested by Hoek and Diederichs (2006) for different disturbance factor (D):

$$E_{rm} = 100 \left(\frac{1 - D/2}{1 + e^{((75+25D-GSI)/11)}} \right) \quad (4)$$

As Fig. 13 shows, there is a good agreement ($R^2 = 0.74$) between the overall modulus of deformation of the rock mass and GSI when disturbance (D) at the test sites is assumed to correspond to 0.05. Using the best fit curve, the expected ranges of deformation rock masses were calculated using the suggested GSI value in Table 4. Average

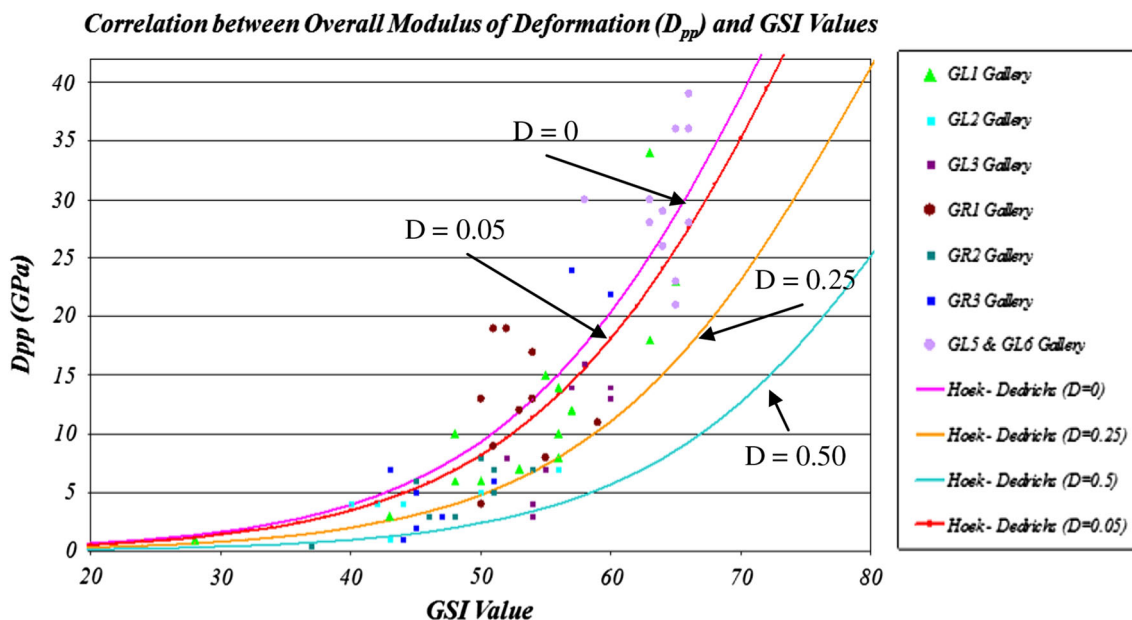


Fig. 13 Correlation between overall modulus of deformation (D_{pp}) and GSI values for plate load tests carried out at Bakhtiary dam site, along with the family curves based on Hoek and Diederichs (2006) simplified formula

value of rock deformation in Sv2, Sv3 and Sv4 rock masses with $GSI_{ave.} = 52$ at the dam foundation would be $E_{rm} = 10$ GPa and for the Sv5 and Sv6 rock masses with $GSI_{ave.} = 60$ in the underground powerhouse area would be as high as $E_{rm} = 18$ GPa.

Conclusions

The 325 m high Bakhtiary arch dam will be constructed on the siliceous limestone of the Sarvak Formation in the northwestern part of the folded Zagros, in southwest of Iran. The complicated geological conditions and structures at the dam site, have necessitated very extensive geotechnical investigations. The surface and subsurface investigations such as core drilling and logging, water pressure tests, geological mapping of exploratory galleries, discontinuity survey and in situ rock mechanical tests are unprecedented in dam site investigation. From these investigations, the following conclusions and statements can be made:

- Based on the tectonic history of the region, the Giriveh-Siah Kuh duplex-anticline and the F1–F3 fault system are interpreted as first-order tectonic structures whilst the chevron fold zones, kink band zones and the joint sets are regarded as second- and third-order structures, respectively.
- The RQD values in the rock mass at the dam site generally rate as good to excellent, and rock masses with very low RQD values have the least frequency in all locations and rock units.
- Because of the rock mass deformation within the kink band zones and a slight degree of dissolution along the joints, the permeability of the rock mass at the dam site is variable. That said, the permeability of the units Sv1 and Sv2 in most cases is low (≤ 10 Lu), whilst the permeability of units Sv3 and Sv4 is high and very high, and in units Sv5 to Sv7, it is very low and low.
- Local disturbance of the rock mass within the kink band zones decreases the rock mass quality and increases the permeability of the rock units.
- Rock mass classifications at Bakhtiary dam site show fair to good quality rock masses at the dam site.
- From the plate load tests results, a site-specific correlation was developed between the overall deformation modulus of the rock masses and the corresponding GSI values assuming a disturbance factor of $D = 0.05$. From the best fit curve, average values of deformation modulus of rock masses were estimated which are 10 GPa for Sv2, Sv3 and Sv4 rock units and 18 GPa for Sv5 and Sv6 rock masses.

Finally, according to the estimated geotechnical parameters at the dam site, it is concluded that the rock

mass condition is favorable for construction of Bakhtiary arch dam with a height of 325 m at this site.

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