ACTIVE FAULTING AT THE GOTVAND DAM SITE BASED ON SEISMIC AND GEOTECHNICAL DATA

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Keywords: Active Faulting, Geotechnical Properties, Seismic Data, Pir-Ahmad Fault, Gotvand Dam

ABSTRACT

Active faulting and subsequent movements in dam foundations can cause structural distortions. Regarding to dam safety issues, faults with surface breaking and potential block movements are the main point of interest and accordingly should carefully be studied, especially on the field. The Upper Gotvand dam is the highest rock fill dam with clay core in Iran which was constructed over Karun River in the southwest of Khuzestan Province. Its location in the Zagros active belt as the most active seismotectonic zone of the country had some problematic effects on it including stability of the abutments and seepage potential through the foundation and abutments. The dam is underlain by the conglomeratic Bakhtiari Formation overlying the sandstones of Agha-Jari Formation. The right abutment of the dam is composed of a highly fractured and displaced mass which is a suitable situation for seepage. This fractured zone is the result of Pir-Ahmad thrust fault which rid Gachsaran Formation of Miocene Age over Bakhtiari Conglomerate of Pleistocene Age. The fault is described as a branch or the continuation of famous Lahbari active fault with nearly 70 km length and is the main reason for such failure. Geotechnical section along the dam axis indicates four along strike faults near the right bank and sharp changes in dip of bedding along the dam axis. The Agha-Jari layers are very tight beneath the dam axis with a 30° inter-limb angle indicating a shevron fold. Also a fault trace was recognized beneath the river bed passing through these layers. The whole region is affected by a N-S basement tectonic lineament named here as Lali-Ahvaz trend. Regarding to the available research articles, the Pir-Ahmad fault was not considered in the stability analysis of the abutment, so a revision of dam stability seems crucial for future seismic events.

INTRODUCTION

Geological conditions especially geologic structure play key role in prediction of future behavior of dams and possible seepage and stability problems beneath their foundation or within their reservoirs. The geological structure of an area could play a key role in the stability of a given site particularly a dam site. The Upper Gotvand dam as the highest rock fill dam with clay core in Iran, is located in Khuzestan Province of southwest Iran. It was planned to produce electrical energy, flood control, water regulation and tourist attraction. Its location in the most seismotectonically active zone of the country had some problematic effects on it including stability of the abutments and seepage potential through the foundation and abutments. This is the main concern of this study to investigate the role of geological structure on geotechnical properties of the Upper Gotvand dam site and relevant instability issues.

Khuzestan Province is located in and the Simply Folded Belt (Falcon, 1974) of the Zagros Fold-Thrust Belt. It is comprised of parallel, long anticlines and synclines; the former shows topographic crest lines, while the latter coincides with trough lines. The studied area is located where the Karun River enters into Khuzestan plain at the end of the above zone (Figure 1). The existence of plastic to semi-plastic lithologies among the stratigraphic sequence is also important due to their great role on the formation of local or regional structures (Barjasteh, 2012a).

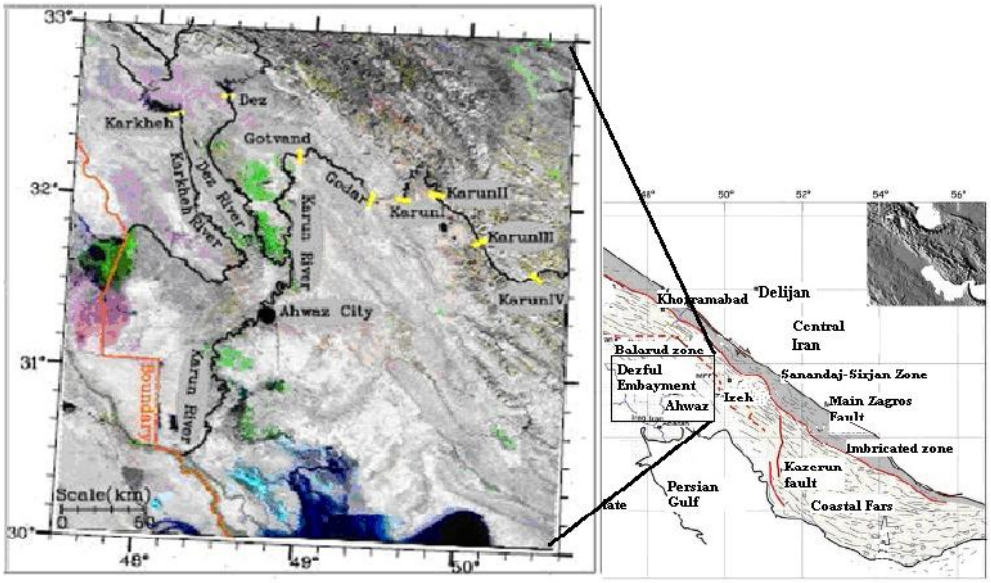

Figure1. The location of the Upper Gotvand dam over Karun river (http://en. iwpco.ir/) in the Zagros Fold Belt

The Upper Gotvand dam was constructed across the Karun River, in the north of Shushtar city. It is a 178 m high earth dam with central clay core. It belongs to a series of cascading dams constructed over the longest and biggest river of the country i.e., Karun river. The most outcropped lithologies in the area, from older to younger, are Asmari Limestones, Gachsaran Evaporites (Gs), Mishan Marlstones (Mn), Agha Jari Sandstones (Aj), Bakhtiari Conglomerates (Bk) and Quaternary deposits. The dam site foundation was constructed on the Agha Jari Sandstones but, its abutments are composed of Bakhtiari Conglomerates (Figure 2). This fractured zone was formed due to the action of Pir-Ahmad thrust fault. The whole region is affected by an N-S basement tectonic lineament introduced here as Lali-Ahvaz trend. Here, active faulting and folding at the dam site will be described and discussed based on different seismic and geotechnical available data.

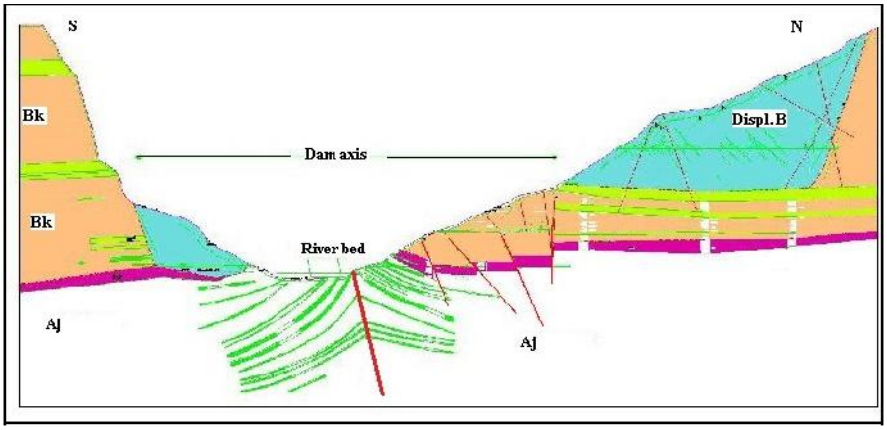

Figure 2. Simplified geological cross section along the dam axis with location of the observed faults in red color (modified after Ahmadi et al., 2008)

DAM SITE GEOLOGY

The Upper Gotvand dam is situated in south west of Iran and constructed on Karun River in 382 km from the estuary. The dam site is located 25km far from Shushtar city, in geographical eastern longitudes of 49°, 48' to 59°, 48' and geographical western longitudes of 32°, 12' to 32°, 17' and has aimed to produce energy. Flood control and control of water, discharge from upstream dams, water regulation and tourist attraction, are the other objectives for constructing the dam. The dam foundation and part of the right abutment is underneath by Agha-Jari Formation which is folded and faulted, with bedding planes and joints inclined with varying dip angles (Figure 3).

Agha-Jari rocks contain veins of gypsum usually associated with clay stone beds. They are naturally soluble and can be suitable for seepage. The left abutment is composed of Bakhtiari Conglomerates that are almost horizontal. It also composed part of the right abutment as a dislocated and ruptured block. Along the northern margin of the river, Gachsaran layers are thrust over the Agha-Jari layers by Pir-Ahmad fault. Most of the geological boundaries along Gachsaran- Bakhtiari contact show evidence of thrust faulting. Its lithology consists of gray, calcareous sandstone with gypsum veins and red marlstone and siltstone. The upper part of Agha Jari Formation (Aj) consists of buff, weathering, gypsum-veined siltstone and silty marl with inter bedded sandstone, and upper part is formed by pebbly sandstone and siltstone assigned a locality name, the Lahbari Member (Lb). The maximum thickness of the veins is reported to be 2 cm and even wider that appear as thin films on the beddings and along joint planes. The latter ones were formed subsequently and indicate the dissolution of gypsum and re-sedimentation in the joints. In general, gypsum is encountered below 25 m deep.

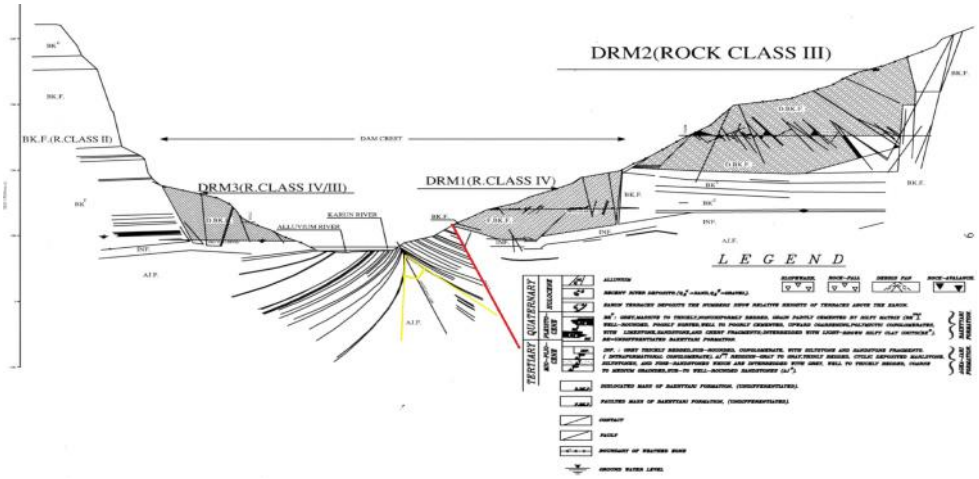

Figure 3. Longitudinal geological section of the dam showing classified rock masses. Red and yellow lines indicate fault trace and fold inter-limb angle, respectively (modified after Shahrokhi, 1994)

Bakhtiari Formation (Bk) was named after the name of Bakhtiari tribe in the north eastern Khuzestan province. The name Bakhtiari was first applied to the chert and limestone conglomerates inter bedded with sandstone that lying unconformably upon the Fars (Agha Jari, Mishan and Gachsaran) sediments of the Lurestan and Khuzestan Provinces. It is almost wholly composed of terrigenous, clastic sediments from silt to conglomeratic boulders. The lower part of the formation consists of massive conglomerate inter bedded with coarse, cross-bedded sandstone and gritstones. Apertures within the Bakhtiari Formation are usually vertical and have relatively large openings and continuity of the apertures often reaches to several meters.

GEOLOGIC STRUCTURE

The dam site region is part of Dezful Embayment structural unit located within the Zagros Simply Folded Belt (Berbrian, 1995). 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. The river bed is occupied by a small anticline composed of Agha-Jari layers with an E-W trend not consistent with general folding trend of the belt. The fold axis of this anticline is parallel with a fault having the same E-W trend. Accordingly, it can be classified as fault related fold (Van der Pluijm and Marshak, 2004) regarding the existence of fault trace beneath the river bed. Besides, it can be more accurately categorized as a fault propagation fold. The action of Lahbari and Pir Ahmad thrust faults in the south and north of the anticline respectively, caused severe compression resulted in tight folding of the Agha-Jari layers. Several sheared and fractured zones observed during foundation excavations and drilling emphasized the subject (Shahrokhi, 1994). The topographic profile of region clearly shows its anticlinal structure (Figure 4). Simultaneous compression of the competent sandstone layers and incompetent siltstone and mudstone layers in the Agha-Jari Formation caused flexural-slip along the bedding plane, proved by numerous slicken – sided surfaces observed on the formation.

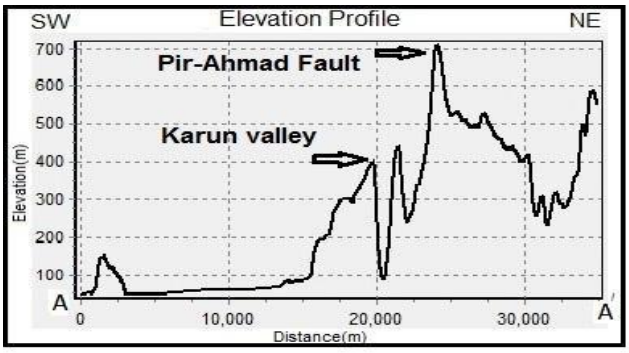

Figure 4. Topographic profile across the Gotvand region illustrating Karun river valley and Pir Ahmad thrust fault location

From the center of the valley toward the right bank, four local faults cut the stratigraphic sequence according to drilled boreholes (Fig.4) that account for sharp and sudden dip changes of the bedding plane. Based on the published data, the inter-limb angle of the fold is about 30° that is classified as a tight fold (Van der Pluijm and Marshak, 2004). The region is cross-cut by a series of thrust faults that give rise to small sub-horizontal southerly and easterly directed displacements (Figs.2, 3 and 5). Moreover, a number of transverse lineaments are observed around the region. The main fault trends are NW-SE to W-E and NE-SW. Along the northern margin of the river, Gachsaran layers are thrust over the Agha-Jari and Bakhtiari layers by Pir Ahmad thrust fault. Most of the geological boundaries along Gachsaran - Bakhtiari contact show evidence of thrust faulting (Fig.4). Fracture study of the region indicated two major sets i.e., SW-NE set and nearly E-W set. The first set is aligned with the direction of maximum compression normal to the general folding trend and the second one that is parallel with regional fault trends (Figure 5).

Field surveys show that the geological structure of the area is not so simple (Barjasteh, 2005; Haji Poor et al., 2010) and different basement trends caused very clear deflections and displacements in the axes of the existing anticlines together with a few number of fracture systems and faults. Morphotectonic analysis based on satellite imagery and RS techniques (Ahmadi et al., 2012) has brought to light a probable N-S orientated tectonic lineament (Barjasteh, 2012) with dextral strike-slip fault. The high SL values around the dam site region indicate high tectonic activity. The Karun River apparently follows the length of this fault directly to the SW of the Anbal piercement upstream of the dam site. The fracture system pattern is fairly aligned with fault trends (Barjasteh, 1994; Haji Poor et. al. 2010). The pattern of joint systems in the region is also exhibiting such trends. Additionally, widespread fracture system in the region and their continuation and extension towards south are observed.

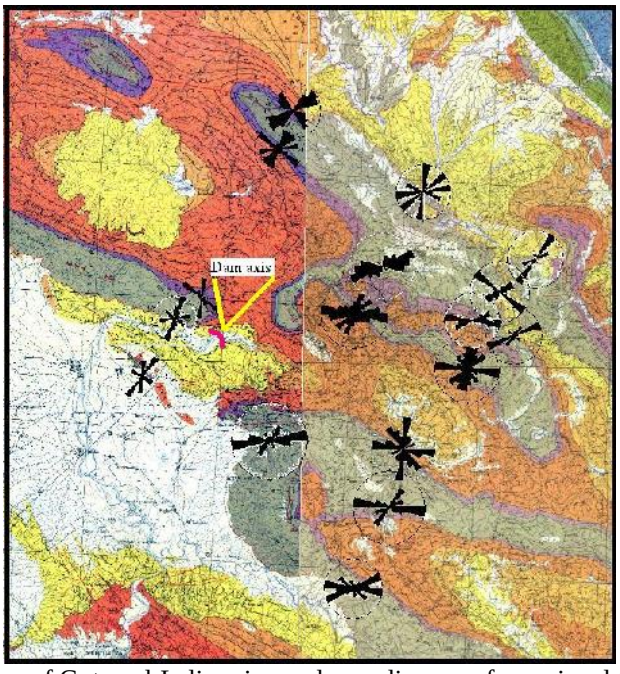

Figure 5. Geological map of Gotvand-Lali region and rose diagrams for regional fracture systems (Haji Poor et al., 2010)

SEISMIC AND GEOTECHNICAL FEATURES

The Upper Gotvand dam is located in the Zagros Active Fold Belt from the seismotectonic point of view (Berberian, 1976, 1977 and 1995) in the northern part of Dezful Embayment structural unit. This is one of the two regional saddles in the Zagros Foredeep and is bounded by the Dezful Embayment fault to the north the Kazerun-Borazjan transverse fault to the east and southeast, segments of the Mountain Front fault to the northwest and the Zagros Foredeep fault to the southwest (Berberian, 1995). Seismicity in the Zagros correlates well with topographic elevations greater than 1.5 km (Tatar, 2102). Fault plane solutions for several of these earthquakes consistently show high-angle (40–50°) reverse faulting and the estimated depths range (Fig.6) from 8 to 13 and have magnitudes that range from 4 to 6. Thus, most of the earthquakes in this region fall close to the interface between the basement and over of an undeformed section. Several authors proposed that the earthquakes are nucleating in the uppermost basement. Recent studies on micro earthquakes around the dam site region proposed a depth of 8 -18 km (Tatar, 2012) for seismogenic layer. The most important faults in the region are: Pir- Ahmad, Lahbari, Andeka, Lali and Shushtar that are of thrust type. The nearest faults to the dam site that could be traced Pir- Ahmad thrust fault. The trace is detected on the north flank of Kuh-e Bard-e Gap within Ab-e Shur valley in the north of the right abutment of the dam which is extended to the eastern margin of the dam reservoir where Ambal salt piercement cropped out (Barjasteh, 2013). Here, the valley has linear E-W trend due to the action of Pir-Ahmad fault. Subsurface structure of the region also proves this orientation. Along the northern margin of the river, Gachsaran layers are thrust over the Agha-Jari layers.

Based on available fault plane mechanisms of the regional events (Figure 6) the maximum principal stress which is due to regional tectonic forces is a horizontal stress with nearly NW-SW direction. Some recent measurements yield an orientation of the maximum horizontal stress with strike direction of N 30◦ ± 5◦ (NE-SW) that is also compatible with the directions indicated by focal mechanisms solutions from earthquakes (Ziaie Moayed et al., 2012).

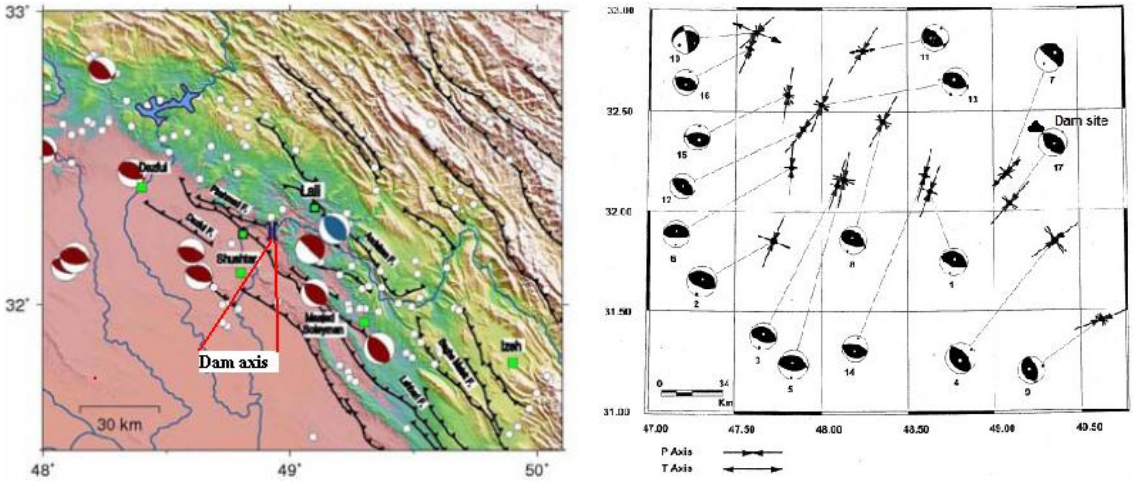

Figure 6. Distribution of the seismic events (left) in the Upper Gotvand dam region (Tatar, 2012) with orientations of compression and tension axes (right)

The strike directions of the regional fractures show almost the same direction with some deviations especially due to local faults (Haji Poor et. al., 2010). However, no detail fracture analysis particularly on neotectonic fractures has been reported up to now and seems to be crucial for future research.

Since the dam site area is recognised by tight folding especially, evidence of slip along the bedding plane of Agha Jari Formation, so possible fault creep along the bedding plane is almost reasonable (Allen and Cluff, 2000). Peak Ground Acceleration Estimation of the Upper Gotvand Dam indicated high MCE values (Maleki and Behnam, 2005) which are questionable regarding to apparent simple structure of the region. Regarding to the geological structure around the dam site and occurrence of Pir -Ahmad and Lahbari faults and possible branching of theses faults beneath the dam foundation as revealed by geological and geotechnical sections of the dam axis, all branch faults may not be considered equally as hazardous as the main break (Allen and Cluff, 2000; Zania et al., 2008; Wieland, 2005, 2009). The available data on static and dynamic analysis of dam foundation and right abutment do not illustrate the inclusion of such local and

regional faults in the stability analyses of the dam site (Nateghi and Kiyani, 2008; Ahmadi et al., 2008; Mahmoodi Dovom Niasar et al., 2010; Amin Poor et al., 2008).

As noted above, the Upper Gotvand dam site was constructed on the Agha Jari and Bakhtiari Formations as shown in (Figures 3 and 4). Geotechnical drillings indicated that the rock in the right abutment is highly disturbed, displaced and fractured. Some faults cut the rock layers from the valley center toward the right abutment (Figure 4). A sharp fault perpendicular to the dam axes cuts the bed rock beneath the river (Shahrokhi, 2000; Ziaie Moayed et al., 2008). Three joint sets were measured in Agha Jari Formation which are mostly sheared and slicken- sided. Their surfaces are generally polished and filled with gypsum and clay. Their very close spacing indicates the existence of a shear zone. The RQD values reported are varying extensively and decrease significantly with depth (Shahrokhi, 2000; Nateghi and Kiyani, 2008) and ranges between 10 to 100 % (Fig. 8). The right abutment is faulted (Barjasteh, 2012) and a dip of 75° towards north was measured for it. The joint sets measured in Bakhtiari Formation are divided in two sets, one parallel to the river direction that is parallel to local fault trends and another that is normal to the river direction. This set is almost parallel to the direction of the general compressive stress, i.e., direction of shortening in the Zagros Fold Thrust Belt. The RQD values in Bakhtiari Formation are generally less than 50% (Figure 7). A detailed analysis of the geomechanical parameters of the dam has been done based on the drilling boreholes (Shahrokhi, 2000).

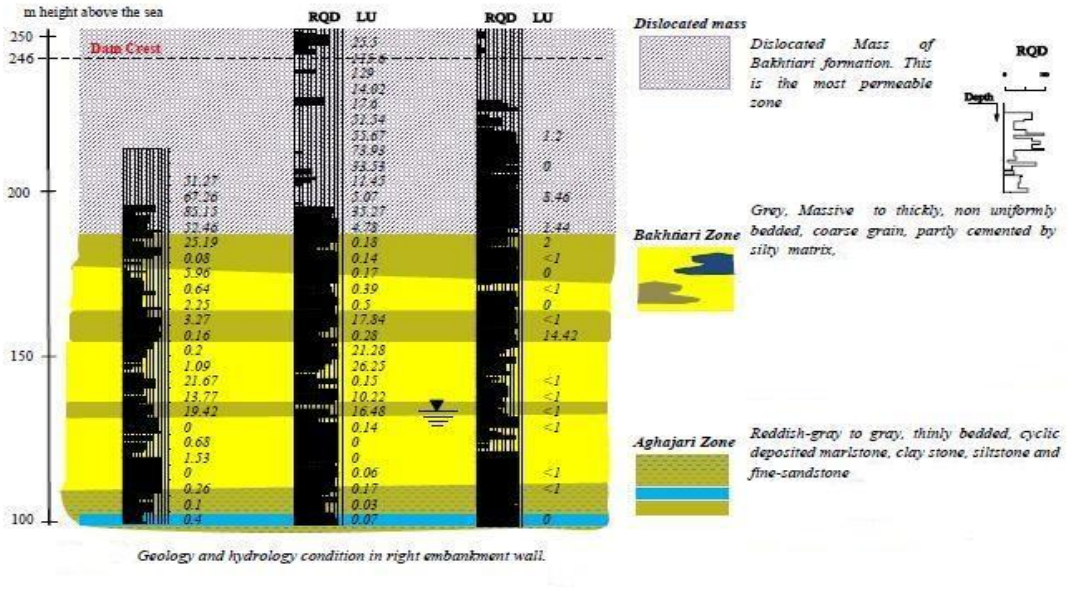

Figure 7. Geotechnical section along the right abutment (modified after Yaghoobi Rafi, 2010)

CONCLUSIONS

Seismic and geotechnical data proved the presence of branch faults in the Upper Gotvand dam site. The river bed is occupied by a small anticline with an E-W trend not consistent with general folding trend of the belt. The fold axis of this anticline is parallel with a fault having the same E-W trend and can be classified as fault related fold or more accurately as a fault propagation fold. The dam site area is recognised by tight folding especially, evidence of slip along the bedding plane of Agha Jari Formation, so possible fault creep along the bedding plane is almost reasonable. The joint sets in Agha Jari Formation are mostly sheared and slicken- sided with polished surfaces filled with gypsum and clay. Their very close spacing indicates the existence of a shear zone. The RQD values reported decrease significantly with depth and ranges between 10 to 100 %. As the right abutment is faulted, it is not clear that the branches of a more significant "main" feature i.e., Lahbari Fault are less active. The available data on static and dynamic analysis of dam site did not illustrate the inclusion of such branching faults in the stability analyses, they should be considered (Wieland, 2005, 2009) equally as hazardous as the main break because, the possibility of future displacements on these branch faults can be dismissed if they have not broken sympathetically with the main fault over a sufficiently long period of time.

Another dismiss in the analyses, is possible fault creep phenomenon that seem to be investigated in near future especially for operation time of the dam. Finally, reservoir-triggered seismicity of the region should be re-assessed considering new founding about folding and faulting in the dam reservoir.

ACKNOWLEDGEMENT

The author wishes to thank his colleagues at Geology and Geotechnics Office, Khuzestan Water & Power Authority (KWPA) for field surveys and valuable comments. He also expresses his thanks to Mrs. R. Ghilav of the Technical Office for helping in review the manuscript.

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