Geological control on the operational behavior of Masjed -e Soleyman Dam, Iran

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ABSTRACT: This article is aimed at study the role of geology on the recent behavior of Masjed-e Soleyman (Godar-e Landar) Dam in Khuzestan Province, south west of Iran. The dam which is a rock fill type has a height of 177 m with a 230 million-m³ reservoir. The foundation rock of the dam is composed of sandstones and conglomerates. Andeka active fault in the north of the dam site is a major structure that affected the dam site geology. Recent monitoring data indicated that powerhouse and transformers caverns suffer severe high stresses on their roofs due to swelling of a claystone layer atop the caverns. Excessive rock mass displacements which caused shotcrete cracking and bolt failure can be seen in some parts of the powerhouse cavern. This article discusses the possible relationship between the geological setting and the observed problems with special emphasis on the powerhouse cavern.

Keywords: Operational behavior, geologic structure, lithology, Andeka Fault.

1 INTRODUCTION

Exceedingly growth of hydro power plants and dams in Iran due to daily increase of water and energy demand during last decades necessitated construction of such civil structures in the country. Masjed-Soleyman (Godar-e Landar) dam, which is a rock fill type, is one of the biggest hydro power projects of the country located at north east of Masjed-Soleyman city in Khuzestan Province, south west of Iran. The dam is 480m long and 177m high with a 230 million-m³ reservoir. The underground power plant, at the depth of 250m, includes a 154.5m x 30m x 43m powerhouse cavern and a smaller size transformer cavern. Four 250 MW generator units are installed in powerhouse cavern (Emadali et al. 2017; Jafari 2003) and an annual 3,700 million kilowatts per hour of hydroelectric power energy. At the end of the fall of 1995, the construction of the dam was started in a dry area following completion of the upstream cofferdam that was topped out at the end of November 2000 at a maximum height above foundation of 177 m (Safi et al. 2006). Reservoir filling started on December 2000 with an exceptionally rapid rise of approximately 6 m per day. The reservoir level eventually arrived at an elevation of 371 m, one meter below full supply level, on July, 2002.

2 SITE GEOLOGY

Regarding to the role of the geological conditions on dam behaviour (Barjasteh 2019) a summary of the regional geology relevant to assessment of the stability conditions of the dam with especial emphasis on its Powerhouse caverns, is presented here with attention focused mostly on local geology. From the structural-geology point of view, the general geological setting of the dam site is nearly simple and mostly characterized by a well stratified sedimentary sequence (Barjasteh 2022). While the dam body is on the sandstones of Agha Jari Formation (Lahmeyer & Moshanir Consultant 1992), the power plant caverns were excavated in the Lahbari Member and partly within the Bakhtyari Formation (Figure 1). The former is a member of Agha Jari Formation. The Agha Jari formation is of Late Miocene to Early Pliocene Age and is mostly composed of marls and sandstones with dispersed gypsum intercalations. Here some gravel, mostly consisting of reworked cherts or clay pebbles, is present probably belonging to the Lahbari Member. The powerhouse cavern is situated in intercalations of the said rock types, of different thickness (Figure 2). From geotechnical point of view, the rocks in this area may be divided into two groups. The first type consists of strong sedimentary rocks such as conglomerate and sandstone with good cementation and the second type contains fine grained rocks or mudstones (siltstone and claystone), which are mostly weak and prone to disintegration. The Pleistocene Bakhtyari Formation is consisted of a sequence of conglomeratic layers with irregularly alternating mudstone and sandstone inter-layers (Figure 2). It is of interest to remind that the layers with higher effective porosity seem to be the thin layers occurring inside the conglomerates and sandstones (Barjasteh & Jalilian 2022), where the original matrix had a larger amount of silt and clay. Due to the large amount of carbonaceous material that composes sandstones and conglomerates, some chemical dissolution phenomena are observed at surface. Locally these dissolution phenomena produce true karstic type structures. The presence of open fractures could be relevant especially for hydrogeological aspects as will be discussed in the next sections.

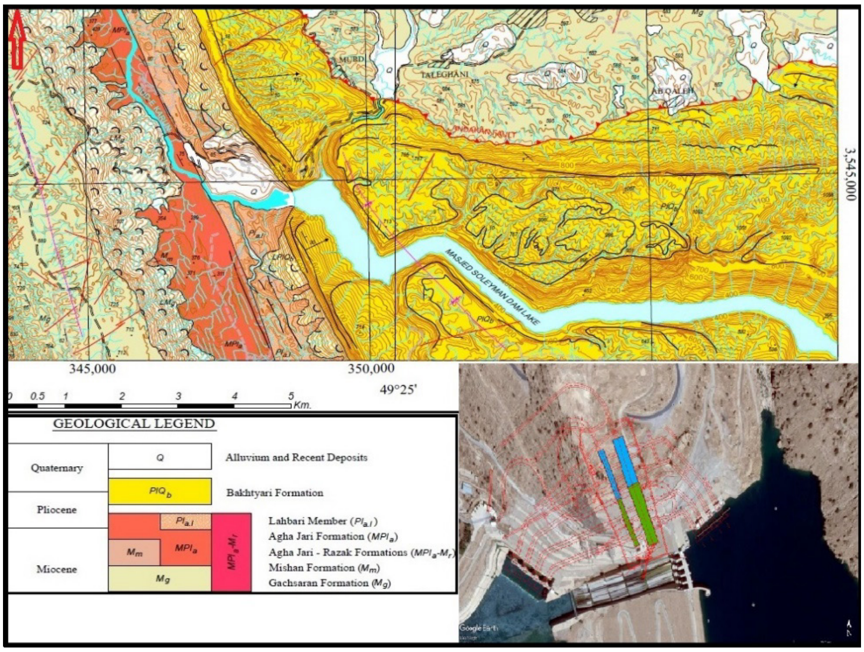

Figure 1. 1/50000 geological map of the dam area (after NIOC 2011) with Google Earth view of the Powerhouse Complex: green: Phase I; blue: Phase II (after Sadd-Tunnel Pars 2018).

The underground caverns and the dam are located in a sector where bedding dips regularly toward NE to ENE (Figure 3) at angles varying between 20º and 45º (160º/20-45ºNE). The broad changes of bedding dip are mostly related to cross bedding and to gentle folding that is very common in Agha Jari outcrops. Two joint sets saying J1 (Longitudinal Joints) 135-145º/40-55ºSW and J2 (Transversal Joints) 230-250º/60-80ºNW seem to be the most frequent ones. The J2 set is almost parallel to the regional direction of compressional stress that is the direction of the Arabian-Iranian Plates convergence. The monoclinal attitude of the bedding planes in the Masjed-I Soleyman (M.I.S) Power Plant area is related to the presence on the SW flank of a regional scale syncline. This is bounded by two faults on the north and in the south of the dam site (Barjasteh 2022). The northern fault (contact between Gachsaran and Bakhtyari Formations) is known as Andeka active fault (Figures 1, 4) with recent seismic events. The study area is subjected to on-going compressional forces, which given rise to the movement of existing thrust faults throughout the basement rocks. The dam site is located in an active seismic region and its seismic hazard and risk rating is extreme (IV) according to the ICOLD recommendation. Based on statistical, probabilistic and deterministic methods, the peak horizontal and vertical ground acceleration (PGA) obtained 0.26g and 0.19g, respectively for design basis level (DBL) motion (Sadd Tunnel Pars Consulting Engineers 2017). Based on the focal mechanism analyses of earthquakes of happened in 1978, 1985, 2002, 2006 and 2019 around the dam site, the maximum principal stress in all the mentioned earthquakes was horizontal (Azimuth varying between 042 to 069 degrees) with an average direction of almost 055 degrees, i.e. N55E. This direction is approximately perpendicular to the power plant caverns. Slickensides exist along the bedding planes between siltstone/claystone layers. These sheared/slicken sided discontinuities are planar, mirror like smooth and prone to form planes causing rock mass instability, especially when the excavated surface is left unsupported and unprotected.

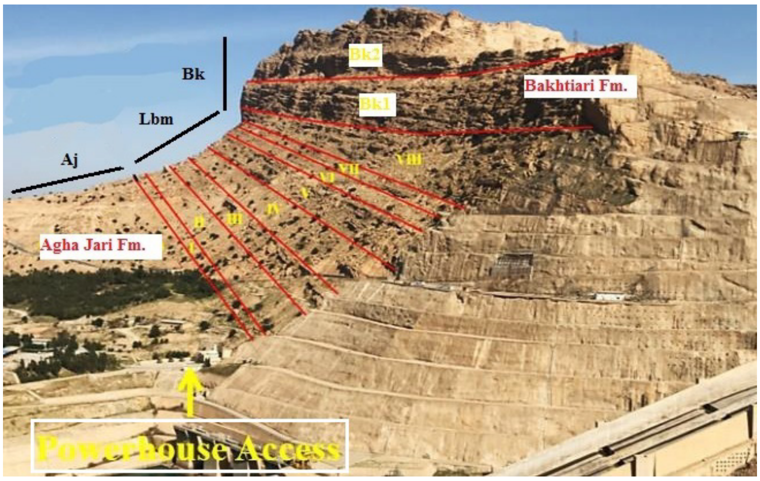

Figure 3. Right abutment geology, NW view. Lbm (Lahbari Member).

The right slope of the Karun River (Figure 1), where the power plant is located is characterized by a NNW-SSE striking ridge related to southwest, by a steep, sub-vertical cliff that becomes gentler approaching the bottom of Karun valley. The ridge has cuesta-type morphology with a steep slope to SW and a gentle slope to NE (Figure 4). In all the southwestern portions of the slope, close to the Karun River, the Bakhtyari formation crops out and is characterized by a general state of slope instability. Open fractures, block sliding and rotation are the rule in this portion of the slope. The trend of these open fractures coincides with J1 (Longitudinal) set of the dam site. The hydrogeological conditions in the M.I.S Power Plant area (Figure 2) where the Powerhouse and Transformer caverns are located is in favor of a low rock mass permeability at depth (area of the Powerhouse cavern) where some more permeable thin layers exist, mostly limited to main boundaries between different lithological units (conglomerates and sandstones versus siltstones - mudstones). The presence of a substratum with open fractures and block landslide deposits on top allows the formation of a thin aquifer layer capable of capturing meteoric waters and release them gradually to the underlying less fractured substratum. Around the caverns, mudstone is exposed in three clearly distinguished layers (Figures 3, 4). The upper layer intersects at the roof of the Powerhouse cavern and at the transformer cavern walls. The lower layer intersects the draft tube level. The intermediate mudstone layer intersects the upstream and downstream walls of the Powerhouse cavern. Mudstones are variable siltstones and claystones with calcite and dolomite nodules. Two sequences of sedimentation can be recognized at the site from an undulating contact between the mudstone and the overlying conglomerate layer. Several mudstone layers are separated by sandstone and conglomerate layers and lenses with variable thickness. In fact, presence of a substratum with open fractures and block landslide deposits on top allows the formation of a thin aquifer layer capable of capturing meteoric waters and release them gradually to the underlying less fractured substratum.

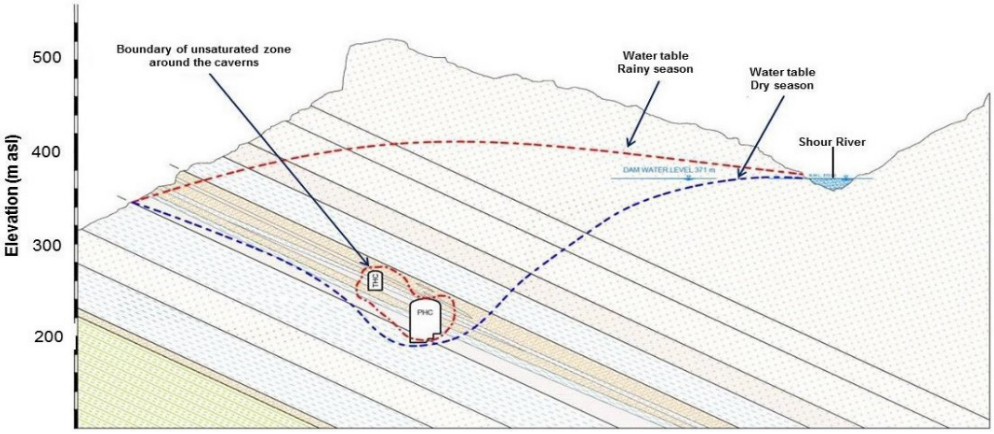

Figure 4. Geological cross section across the caverns.

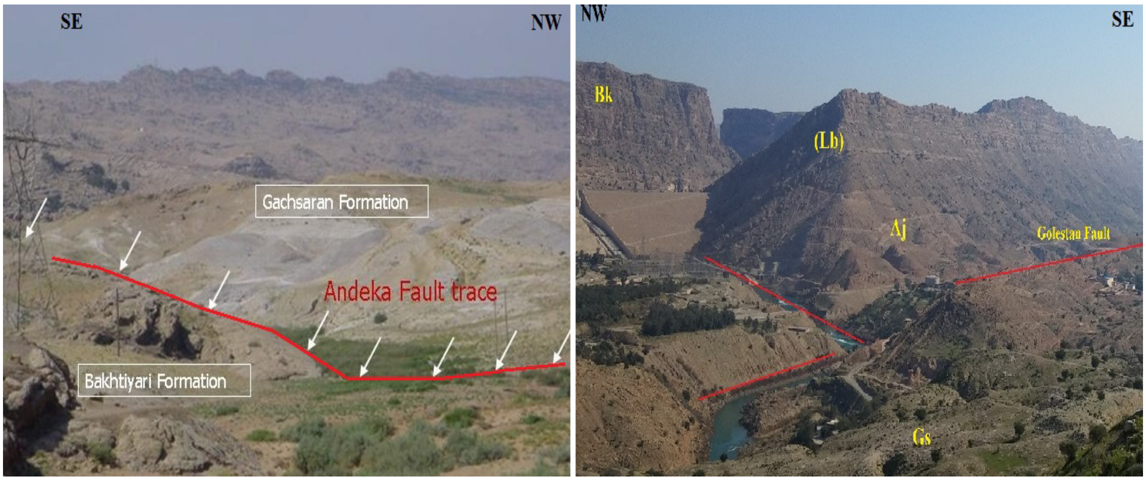

Figure 5. Exposure of Andeka and Golestan Faults at north and south of the dam site, respectively.

Based on the water pressure tests performed, for units of the Lahbari Member (Figure 5), the average conductivity value above 60 m depth is 6.8x10-6 m/s, while below 60 m it decreases to 2.8x10-7 m/s. During excavation and construction of the Phase I caverns, a maximum inflow of 1-2 l/s was reported, with a more significant seepage occurring at the contact between conglomerates and sandstones with the interbedded mudstones acting as impervious layers (Moshanir & Lahmeyer International 1993). A saturated zone with a water table in equilibrium with the Karun River existed in the right slope before the excavation of the underground caverns, with both permeable and less permeable layers saturated, with active flows being concentrated only along the more permeable layers. Expectedly, the ground water table was rather irregular, due to the strongly heterogeneous permeability distribution. After excavation of the tunnels and caverns and the impoundment of the reservoir, the groundwater conditions in the area changed completely and today a rather complex distribution of the water heads is present. Some localized flow takes place along the more permeable layers and reaches the caverns. With the above in mind, the ground water table is expected to vary considerably during the year due to a seasonal change of the climatic conditions.

3 INSTRUMENTATION OF THE DAM

The instrumentation installed, at M.I.S dam was evaluated against international guidelines for dam instrumentation (Hager et al. 2021). In general, it would be considered as a well instrumented dam if compared to other rockfill dams of a similar size worldwide (Williams 2004). There are totally 381 different instruments used in the dam body (Sadd Tunnel Pars Consulting Engineers 2020). Six rings of instrumentation were designed for the powerhouse cavern (Figure 6) at chainages: 8, 21,43,71,93 and 107. A set of instrumentation was installed at three positions in the cavern roof (U/S, D/S and centre of the roof). These instrumentations consist of load cells and extensometers. In order to ensure the stability of roof of the extension power house cavern, dywidag brand monobars (15 or 20 m. long) with working load of 624 KN have been used. All the available data and studies from previous reports relate the observed deformations at the time of construction and at present with the weak siltstone/mudstone layers which characterize the sedimentary sequence hosting the caverns (Stabel & Samani 2003, Jafari 2003, Safi et al. 2006). The extensometers installed at the roof of the Phase I Powerhouse cavern show an increasing trend in the displacement values in the downstream and at the roof. The increase in the displacements at the downstream wall of the Transformer cavern is due to the presence of clayey layers in this area. A number of load cells installed on the anchors at the roof of the Phase I Powerhouse cavern undergo increasing loads indicating the likelihood of instability. The presence of clayey layers on the downstream wall of the Phase I Transformer cavern is responsible for the increase in load observed. The largest displacements take place in the extensometers at the downstream wall and at the roof center of the Phase II Powerhouse cavern. An increasing trend in the displacements occurs on the downstream and upstream walls of the Transformer cavern. The large displacements are here again related to claystone and siltstone layers.

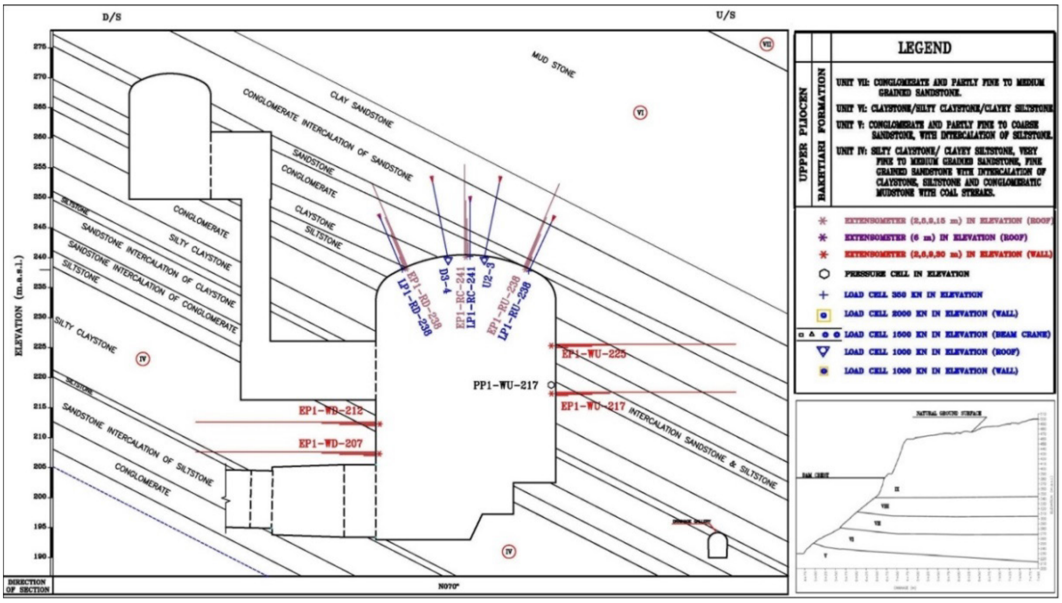

Figure 6. Geological section along Powerhouse cavern (modified after Sadd Tunnel Pars Consulting Engineers 2020).

A number of the load cells at the downstream wall and at the roof center of the Phase II Powerhouse cavern show loads higher than the design capacity of the anchors. This is also the case of the load cells on the anchors on both the downstream and upstream walls of the Transformer cavern. Swelling was to be expected and the swelling tests performed showed that the swelling potential of most of the mudstones is from moderate to high. Hence, it is apparent that the deformational response of the caverns versus time is related to groundwater as associated to the swelling behaviour. As mentioned before, the M.I.S Power Plant is in the near vicinity of the Andeka active fault nearly 2.1 km upstream of the dam body and the maximum principal stress azimuth of the area has an average direction near to 055 degrees, i.e. N55E. The activity of this fault along with that of the Lahbari Fault establishes active folding in the region that can impose excess stress on the dam site area.

4 CONCLUSIONS

According to data presented in the above sections, some zones of ongoing deformation are highlighted by the monitoring system especially on the Power plant caverns roof. All available data for deformations observed both at the time of construction and at present day in some way attribute them to varying lithology of the existing rocks at the site. This is related to the presence of mudstone layers inside the sedimentary sequence hosting the caverns regarding their swelling potential along with weak geomechanical characters. The presence of weak layers (especially claystone and siltstone) on the caverns roof resulted in formation of low strength joints which caused instability of the roof. Besides, low mechanical properties of the claystone layers, especially when absorbing water, can result in further roof instability due to drop in the geomechanical values of the rocks. Active folding in the region due to the activity of Lahbari and Andeka active faults can impose excess stress on the dam site area that can result in further instability of the Power plant caverns. Finally, although the performance of the embankment dam is considered to be satisfactory, the increasing trend of displacement and load on the Powerhouse roof together with local rock falls alarmed the necessity for more detail rehabilitation studies to assure long term stability of the caverns.

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