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Hypogenic Karstification and Conduit System Controlling by Tectonic Pattern in Foundation Rocks of the Salman Farsi Dam in South-Western Iran

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Abstract**—**The Salman Farsi dam project is constructed on the Ghareh Agahaj River about 140km south of Shiraz city in the Zagros Mountains of southwestern Iran. This tectonic province of south-western Iran is characterized by a simple folded sedimentary sequence. The dam foundation rocks compose of the Asmari Formation of Oligo-miocene and generally comprise of a variety of karstified carbonate rocks varying from strong to weak rocks. Most of the rocks exposed at the dam site show a primary porosity due to incomplete diagenetic recrystallization and compaction. In addition to these primary dispositions to weathering, layering conditions (frequency and orientation of bedding) and the subvertical tectonic discontinuities channeled preferably the infiltrating by deep-sited hydrothermal solutions. Consequently the porosity results to be enlarged by dissolution and the rocks are expected to be karstified and to develop cavities in correspondence of bedding, major joint planes and fault zones. This kind of karsts is named hypogenic karsts which associated to the ascendant warm solutions. Field observations indicate strong karstification and vuggy intercalations especially in the middle part of the Asmari succession. The biggest karst in the dam axis which identified by speleological investigations is Golshany Cave with volume of about 150,000 m^3. The tendency of the Asmari limestone for strong dissolution can alert about the seepage from the reservoir and area of the dam locality.

Keywords**—**Asmari Limestone, Karstification, Salman Farsi Dam, Tectonic Pattern.

I. INTRODUCTION

THE Zagros Fold belt of south-western Iran is a structural unit trends northwest-southeast characterized by the successive asymmetrical anticline-syncline structures with increasing deformation towards the northeast and host a folded sedimentary sequence from the Permian to Recent period. The Asmari Formation limestone of Oligo-miocene is the most important carbonate succession in the Zagros Mountain range, both as an oil reservoir and karst aquifer. The Salman Farsi dam site is situated on the northern flank of the Changal Anticline in the Fars Province of Iran. The Asmari Formation limestone forms the dam foundation rocks and is divided into three units from an engineering geological point of view and is also intersected by several vertical to subvertical transverse faults. The hydrogeological and speleological investigations indicate the Asmari limestone was submitted to extensive karstification processes (hypogenic karsts) due to ascending hydrothermal solutions originating at depth. Well developed subvertical fracture systems, together with frequent and steeply dipping joint systems along the bedding planes create a fully connected network for preferential water flow i.e. the limestone rock mass was fully exposed to karstification processes and turbulent underground flows eroding the walls of initial karst conduits to produce large channels and caverns. Most studies of karst systems are concerned with shallow, unconfined geologic settings, supposing that the karstification is ultimately related to the earth's surface and that dissolution is driven by downward meteoric water recharge. Such systems are epigenic or hypergenic [1].

The non-homogeneous character of the karst formations, irregular spatial distribution, deficient data, limited inspection due to time and cost restrictions, and unreliable models are the main causes of leakage at karst dam sites. The high permeability zones are local, representing a small percentage of the total karst area. Hence uncertainty analysis is an applicable technique in estimation of dam safety issues caused by leakage [2].

II. GEOLOGICAL SETTING

The *Salman Farsi* gravity arch dam is constructed on the Ghareh Agahaj River at the entrance to the Karzin Gorge about 140km south of Shiraz city and 12km northeast of Ghir in the Zagros Mountains of Iran (Fig. 1). This tectonic province is characterized by a simply folded sedimentary sequence, of which only post Permian and Oligocene to Pliocene rocks are exposed.

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Fig. 1 Salman Farsi dam project located 140km south of Shiraz in the Fares Province of Iran

The dam constructed on the northern flank of the Changal Anticline which is an asymmetrical fold structure with northwest-southeast trend constitutes the most significant structure with regards to the tectonic and hydrogeological setting of the area (Fig. 2).

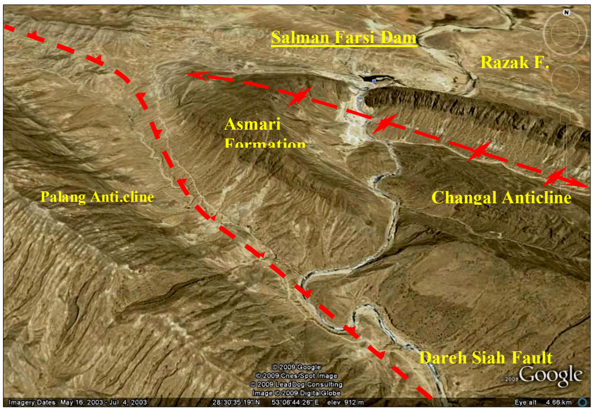

Fig. 2 Satellite image of Salman Farsi dam project constructing on the northern flank of Changal Anticline at the Zagros folded belt

The dam foundation rock is Asmari Formation limestone of Oligo-miocene which comprise of limestone, marly limestone, dolomitic limestone and marlstone. Impervious marlstone, marlylimestone and shale of the Pabdeh Formation constitute the core of the anticline and create a suitable watertight underground barrier.

The dam with a gated spillway has a height of 125m and reservoir 1400 million m^3. Other structures comprise of upstream/downstream cofferdams rockfill and a diversion tunnel in the left flank. The powerhouse contains two small generator units with a total capacity of 13MW electrical energy (Fig. 3).

Fig. 3 Salman Farsi (Ghir) dam is a 125 m high concrete gravity arch dam within the Ghareh Agahaj River (northeast view)

According to the engineering geological characteristics of the rock mass the Asmari Formation limestones divided into three units as follow (Figs. 4 and 5):

- As.3 (upper)

  150m light grey thinly bedded alternation fossiliferous limestone, marl and marly limestone with restricted cavities and fairly impervious. The upstream cofferdam is constructed in this unit.

- As.2 (middle)

  270m thickly bedded crystalline limestone, dolomite, and dolomitic limestone with vastly developed karst features and high permeability. The dam body, diversion tunnel and grouting curtain are situated in this unit.

- As.1 (lower)

  230m regularly bedded fine grained limestone and marls with isolated cavities and low permeability. The power house, downstream cofferdam, diversion tunnel outlet and downstream cofferdam are constructed in this unit.

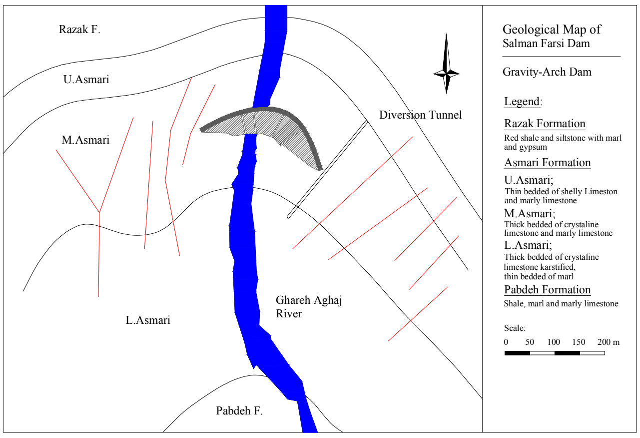

Fig. 4 The geological map of Salman Farsi dam foundation rocks [18]

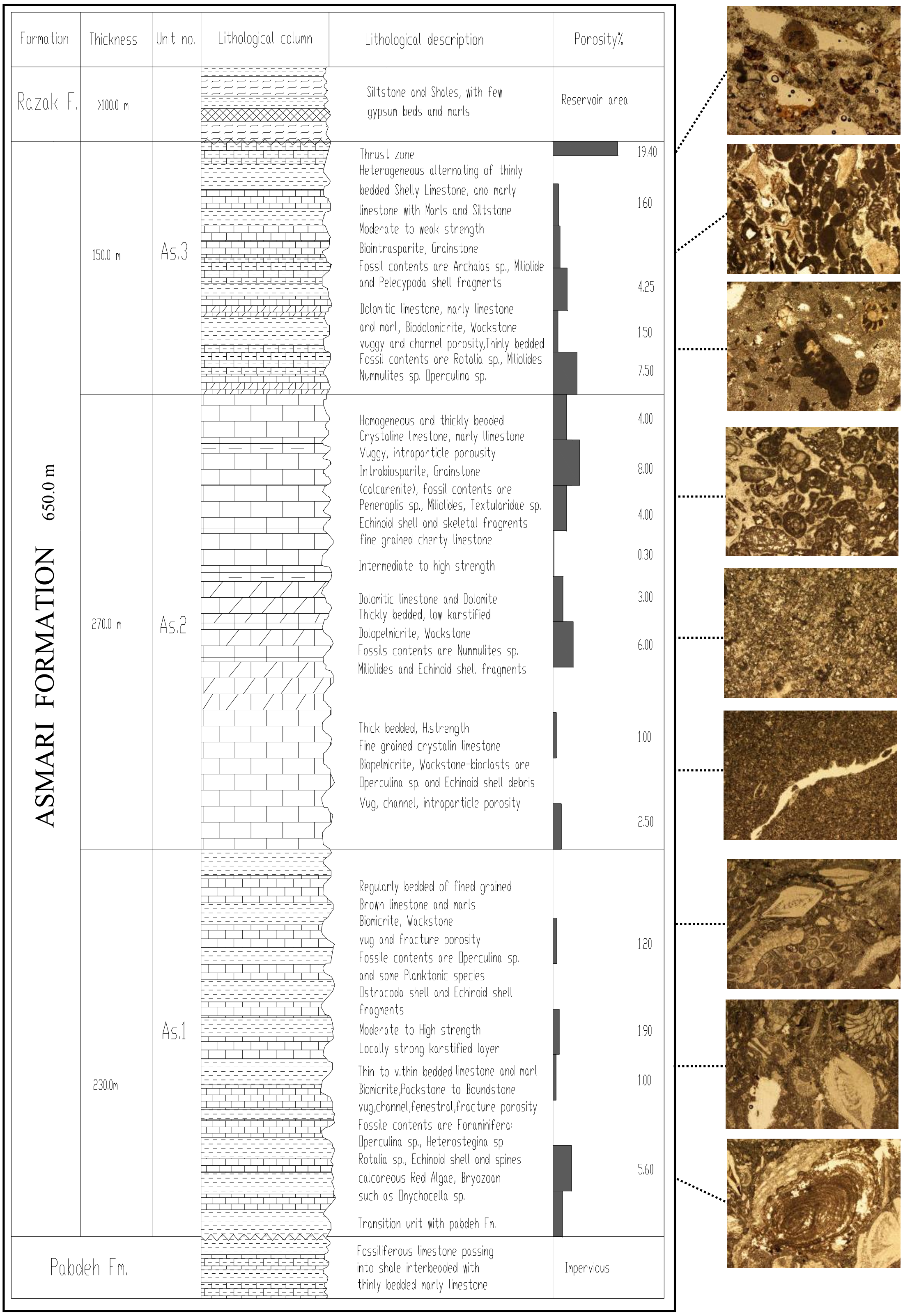

Fig. 5 Lithological column and petrographic analysis of the Asmari Formation at Salman Farsi (Ghir) dam site

III. Petrographic Studies and Porosity Condition

The petrographic characteristics of the rock mass were determined with thin section studies (Fig.5). The analyses are based on Folk and Dunham Classifications [3], [4] which are two important methods in the petrograpic analysis of carbonates rocks. The basic porosity types defined by the

Choquette and Pray chart [5] and finally the percentage of total porosity have been measured by microscopic quantitative method/point-counting [6].

- As.3 (upper)
  Biodolomicrite wackestone to Biosparite Grainstone. Fossil content is mainly foraminifera such as Archaias sp., *Rotalia* sp., *Operculina* sp., *Nummulites* sp. and Miliolide and skeletal debris such as pelecypoda. Porosity features are vug and channel types and vary between 1.5% to locally 19.4% in fractured zones.
- As.2 (middle)
  Bidolomicrite Wackestone to Biosparite Grainstone. Fossil content is mainly foraminifera such as *Nummulites* sp., *Operculina* sp., *Peneroplis* sp. and Miliolides and skeletal debris such as Echinoids. Porosity features are vug, channel and intraparticle types and vary between 0.3% to 8%.
- As.1 (lower)
  Biomicrite, Wackestone to Packstone locally Boundstone. Bioclasts consist of foraminifera such as *Operculina* sp., *Heterostegina* sp., *Rotalia* sp., and Planktonic species, echinoid fragments and calcareous red algae. Porosity features are mainly vug/channel types and vary between 1% - 5.6%.

According to the lithological column of Fig. 5 the porosity values increase locally to 19.4% concerning to the fault zones.

The permeability of the rock mass (derived from lugeon tests) and porosity condition are summarized in Table I. The permeability in the upper and lower units indicate low values due to the impermeable layers such as marly limestone and marl compared to the highly permeable middle part which imply to the well developed karst and conduit systems.

IV. TECTONIC MODEL

The Asmari limestone ridges on both flanks at the dam site are dissected by a subparallel system of vertical and subvertical discontinuities (shears) and small scale faults running across the Changal Anticline axis. The majority is several metres long subvertical with strikes of generally NNE-SSW. Slickensides and bedding offset show a predominant left lateral slip work up to two metres of displacement (Fig. 6).

According to the statistical orientation distribution two main joint structures exist as a strongly developed conjugate sets (Fig. 7).

a) Bedding planes and interbedding discontinuities due to shearing processes during the formation of the Changal Anticline with dip direction/dip of 10°–20°/55°-65°.
b) Vertical to subvertical small scale joints with no considerable movement. Two main joint sets Js.1 and Js.2 with dip direction/dip of 115°-150°/65°-85° and 280°-295°/75°-90° were distinguished.

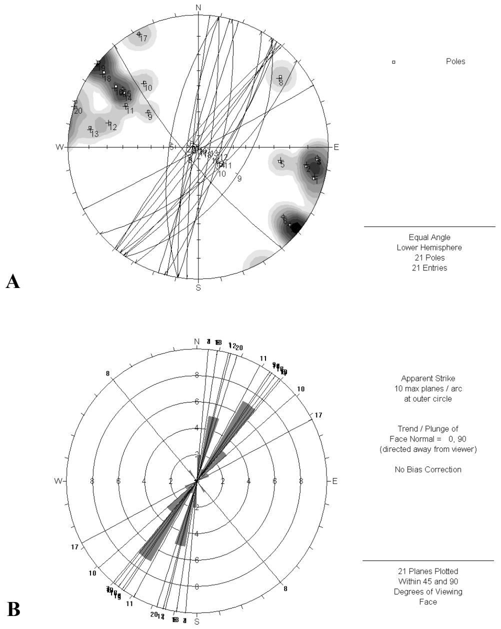

Fig. 6 Stereographic projection of faults (general orientation of small-scale faults) A- Contour plot, B- Rosette plot (Dips©, equal area projection-Schmidt net, lower hemisphere)

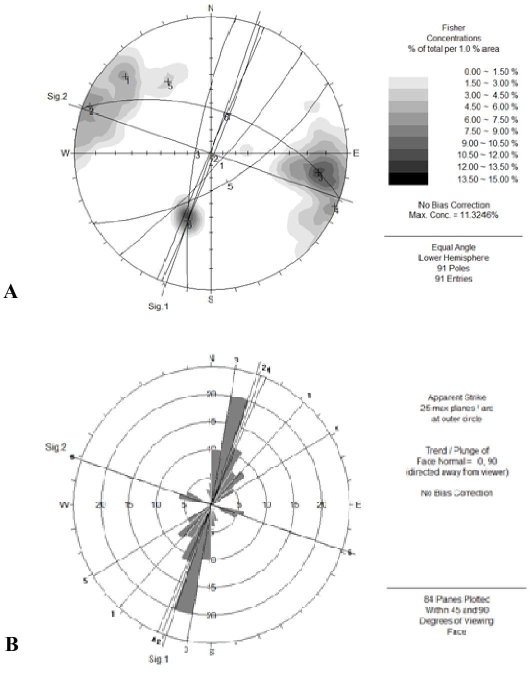

Fig. 7 Stereographic projection of joints sets in the Salman Farsi dam foundation rocks A- Contour plot and B- Rosette plot (Dips©, equal area projection-Schmidt net, lower hemisphere)

These two joint sets and faults formed due to the stress field of the folding stage of the Changal Anticline and are the major cause for the secondary processes of karstification in the Asmari limestone by hydrothermal solutions originates at depth.

V. KARSTIFICATION PROCESS AND KARST OCCURRENCE

Karst is commonly created by the dissolution of soluble rocks including limestone, dolomite and gypsum [7]. Karstification and karstic landforms vary in size and type due to carbonate composition, climate, altitude and geomorphologic evolution [8], [9].

Water draining into fractures begins to dissolve the rock creating a network of passages. Over time, water flowing through the network continues to erode and enlarged the passages; this allows the system to transport progressively larger amounts of water. This process of dissolution controls the development of caves, sinkholes, springs, and sinking streams [10].

Karst features principally occur in carbonate rocks which are considered as true karst [11]. It is genetically classified into two groups:

A. Epigenic karst (Hypergenic)
B. Hypogenic karst

Epigenic karst forms when rainwater becomes acidic as it comes in contact with carbon dioxide (CO_2) in the atmosphere and the soil (by descending groundwater) while hypogenic karst stems from rising groundwater (Fig. 8). The term and hypothesis of hypogenic speleogenesis has been increasingly used over the past two decades, though there is still some doubts over meaning [1].

The occurrence of cross-cutting permeability features e.g. faults strongly affects cave patterns. Geochemical interactions of flow components guided by transverse and lateral permeability conduits verify zones of significant speleogenetic development and influence consequent patterns. The progressive factors such as regional tectonic and geomorphic developments that change flow patterns and setting, as well as development of speleogenesis, also affect cave patterns forming in hypogene settings. In contrast to epigene settings where initial effective permeability structures are exploited by speleogenesis in a very selective manner, hypogene speleogenesis tends to exploit most of the structures within cave-forming zones [12].

TABLE I
POROSITY, KARSTIFICATION AND PERMEABILITY OF THE ASMARI FORMATION

Formation	Unit	Lithology	Porosity%	Porosity type	Karst	Permeability
Asmari	Upper	limestone, dolomitic limestone, marlylimestone, and marlstone	1.5 - 19.4	Vuggy: 68%,	Karstified dissolution cavities	No to L
	Middle	crystalline limestone, dolomitic limestone and marly limestone	0.3 - 8	Fracture/channel: 11%	Chimney and caves 100s m^3	L to V.H
	Lower	fine grained limestone and marlstone	1 - 5.6	Others: 21%	Isolated cavities	L

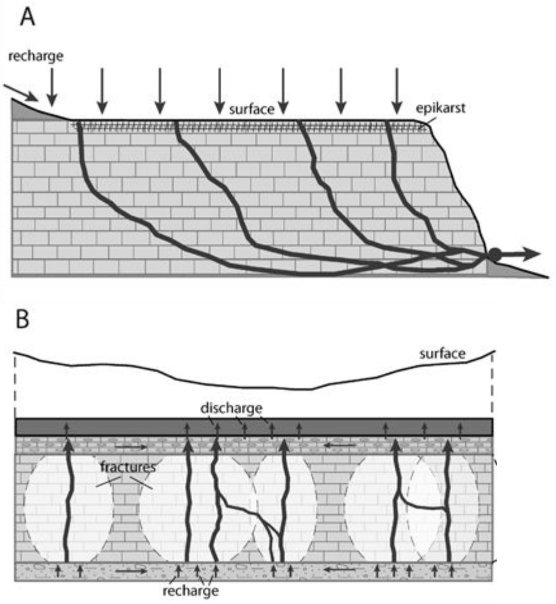

Fig. 8 Conceptual representation of epigene (A) versus hypogene (B) speleogenesis [12]

Two approaches appear in recent works by Ford and Williams [13] and Worthington and Ford [14] cleared hypogenic caves as those formed by hydrothermal waters or by waters holding hydrogen sulfide. Hill [15] tends to narrow the notion of hypogenic karst and speleogenesis allows to H_2S related processes. Palmer [7] defined hypogenic caves more widely, as those created by acids of deep-seated source, or epigenic acids rejuvenated by deep seated processes. Palmer [16] offered the meaning in a slightly modified, broader form: as *hypogenic caves are formed by water in which the aggressiveness has been produced at depth beneath the surface, independent of surface or soil CO_2 or other acid sources.* This modification is important, as it formally allows us to include in the class of features formed by still surface-independent but non-acidic sources of aggressiveness (such as aggressiveness of water with respect to evaporites).

Generally the solvents are endogenous CO_2 related to magmatic degassing or H_2SO_4 originates from sulphide oxidation of evaporites or hydrocarbon at depth. Hypogenic karst derived from a source of aggressiveness produced at depth (CO_2 or H_2S) and linked to confined or rising flow, without the direct influence of surface recharge. It relates almost to the artesian flow, where hydrothermalism is a variant [16], [17].

The hydrogeological features of the Salman Farsi dam site are the result of the regional geological setting. The impervious and compressed anticline core is the barrier for underground water flow from the upper erosion base level to the lower step (Fig.9). A number of springs (thermal as well as meteoric water) discharge along the gorge section upstream of the barrier. It seems as if there is no hydrogeological possibility for the underground water to penetrate downstream. Water flow towards the regional base level (Ghir Plain) is interrupted by a deep long and wide impervious barrier consisting of the Pabdeh and partially of the Lower Asmari formation [18].

A well developed subvertical fracture system, together with frequent and steep joint systems along the bedding planes create a fully connected network for preferential water flow i.e. the limestone rock mass was fully exposed to karstification processes then the turbulent underground water flows eroded the walls of initial karst conduits producing the large channels and caverns.

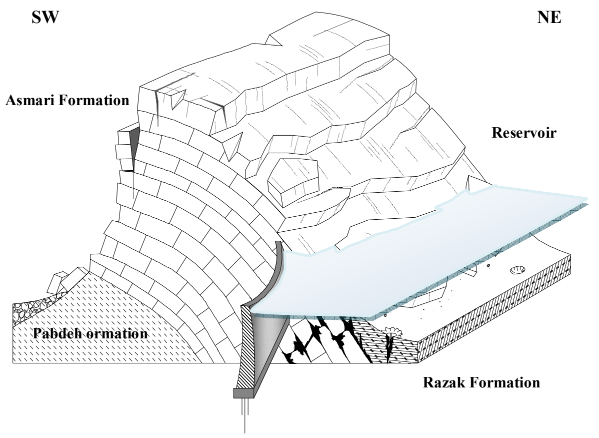

Fig. 9 Block diagram of the Salman Farsi dam foundation rocks on the northern flank of the Changal Anticline. Showing dam body/cut off curtain, reservoir area and distribution of the Pabdeh (marl), Asmari (karstic limestone) and Razak (gypsum) formations

The karstic features developed along these discontinuities and the steeply dipping bedding planes with the intersection of Js.1 and bedding planes as well as faults play the main role in the karstification of the Asmari limestone as well as occurrence of big karsts in the region (Fig. 10). These features may provide a direct hydraulic connection between the reservoir and the gorge downstream of the dam with possible substantial seepage from the reservoir bypassing the dam wall.

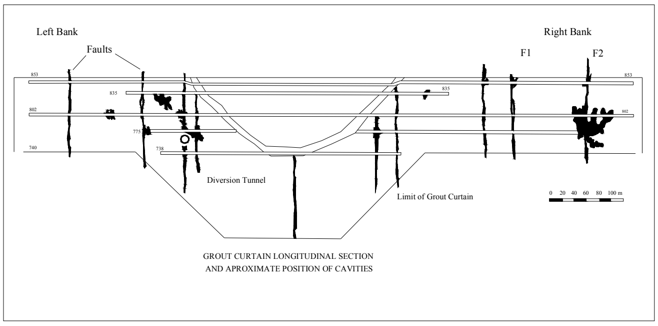

Fig. 10 Schematic presentation of grout curtain longitudinal section and approximate position of cavities at Salman Farsi dam [18]

Commonly the progress of karst features depends on three factors usually; lithology, distribution of rock types and occurrence of discontinuities. There is a general tendency for strong dissolution of the porous, vuggy, micritic limestone compared to the more resistant, less porous, crystalized, fine to medium-grained calcarenite. Fossiliferous and fine grained cherty limestone of the middle unit rarely shows weathering, whereas marls and marly limestones are impervious.

A total 40 springs were recognized at the dam site at river level of which 30 springs are at the left flank and 10 springs on the right flank discharging from the middle part of the Asmari Formation. The springs can be categorized into two groups of cold springs with average yearly temperatures of 23°C to 26°C related to meteoric water and artesian hot springs related to the karst limestone of the central unit with temperatures ranging from 38°C to 40°C. The hot springs play key role to dissolution of the limestone through joints, bedding planes, faults and their intersections [18], [19].

The Asmari Formation mainly shows secondary porosity of vuggy, channel, and cavern types with the main discontinuities, bedding planes as well as fault zones enlarged by dissolution of limestone with well expanded karstification in the middle unit (Fig.10). According to the speleological investigations numerous karrst features have been detected with the largest one 150000 m^3 (Golshani Cave) in the right flank (Fig. 11). Due to the development of marl and marly limestone the karst features are rarely present in the lower and upper part of the Asmari sequence.

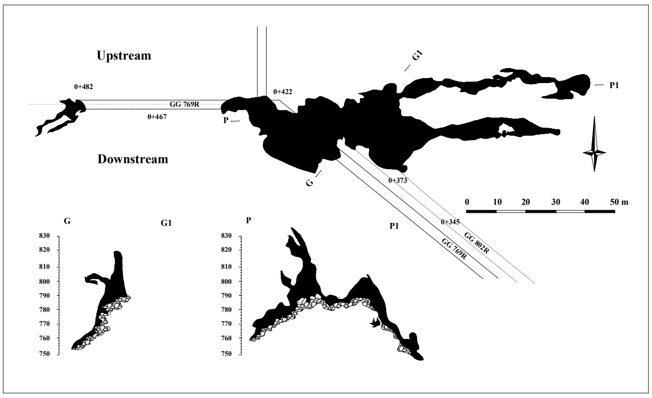

Fig. 11 The geological map of Golshani Cave in the right flank of the Salman Farsi dam [18]

The middle Asmari Formation acts as a preferential permeable zone for aggressive hot water rising through the connected discontinuities. The strength of the rock mass caused the development of interconnected and relatively clean pathways for movement of aggressive water originating at depths (Fig. 12).

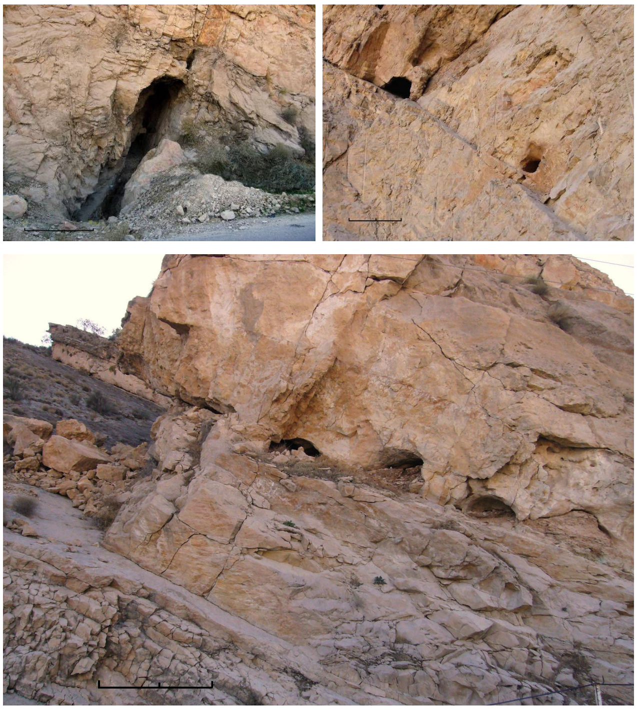

Fig. 12 Some karstic features due to dissolution of limestone along discontinuity surfaces in the upper part of the middle unit of the Asmari Formation. These features constitute a 3D network of channels, which somewhere converge into huge caverns

Parts of the caverns are filled with well-stratified, dense and plastic clays. Karst features are mostly poor with speleothems and very dry and permanent or temporary water absent above the river level. Two various types of karst can be seen: (a) Vuggy porosity and (b) Classical karst porosity. Vuggy porosity is commonly aligned along some layers, but vugs can also be found in a dispersed pattern. The diameter of vugs varies between a few millimetres to about 20cm [19].

The general shape of the karst features results in metres long oblate chimneys of several decimetre diameter following the sharply plunging bedding in the middle unit. It has been suggested that the karst in the middle unit, is a mature system, produced during a period of strong hydrothermal activity, because evidence of extremely mineralized past ground water circulation are common. This theory may be maintained by the existence of hot springs and suggests that the karst should also have expanded in depth. [18].

Klimchouk [12] introduced the following elementary cave patterns for hypogenic speleogenesis:
a) Zones of cavernous porosity
b) Network maze
c) Spongework maze
d) Isolated passages or small clusters of passages
e) Irregular isolated chambers
f) Rising, steeply-inclined passages or shafts
g) Collapse shafts over large hypogenic voids

The cave patterns at the Salman Farsi dam site can according to this classification be categorized in rising, steeply-inclined passages or shafts.

Milanovic [2] reported on the most likely leakage mechanisms from reservoirs in various karst areas of the world. The main causes of leakage at karst dam sites are the non-homogeneous character of the karst formations, deficient data, limited inspection due to time and cost restrictions, and unreliable models. The high permeability zones are localized, representing a small percentage of the total karst area. The risk component could be inevitable despite the very detailed and complex investigation programs, comprising all available techniques. It is not realistic to plan the complete avoidance of risk in karst areas. Hence uncertainty analysis is an applicable technique in estimation of dam safety issues caused by leakage.

The dye-tracer test is one of the most powerful techniques to determine karst development, it is a point-to point connection and it is dependent on the location of injection and sampling points (or boreholes). Therefore, major karst conduits may be missed. Estimation of groundwater flow velocity is one of the main goals of tracer tests. Although the equation for estimation of velocity is very simple, extensive uncertainties may exist in the results of dye-tracing tests [20].

VI. CONCLUSION

The Asmari Formation limestone generally indicates two porosity types of vugy and classical karstic features. The vugy porosity tens of centimeters in size and scattered irregularly along bedding planes plays a less significant role in the hydrogeological conditions of the rock mass as opposed to the classical karst features that are well developed along main discontinuities such as joints and faults and play the key role in hydrogeological condition at the dam site. The karstic process created big caves and interconnected conduit systems by hydrothermal water arising at depth. In this regard the upper and lower units of the Asmari Formation as well as the Pabdeh Formation due to their relatively impervious characteristics allowed the middle Asmari Formation to act as a preferential passage for circulating hydrothermal solutions and the development of hypogenic karst features. Hypogenic karsts genetically expanded below the areal water base level and create a complicated network associated with ascending hydrothermal solutions through important joint and fault system. However hydrogeological investigations such as dye tracer tests and speleological surveys were performed in the dam project but there is uncertainty regarding the irregular distribution of karst features in the non-homogenous rock mass. Water losses can bypass the grout curtain through joints/faults as well as in the reservoir area through the karsts and channels which are not covered by the silty clay or assorted and slightly consolidated slope wash which are adequately thick to withstand the hydrostatic pressure. The heterogeneous nature of the karst structures, deficient data, limited inspection due to time, cost restrictions, and unreliable models are the major causes of leakage at karst dam sites. The high permeability zones are localized and commonly representing a small percentage of the total karst area. Therefore in karstic areas such as at the Salman Farsi dam more detailed investigations will be needed to detect the

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hidden karstic system at the dam locality and in the reservoir area.

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