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RESEARCH PAPER

The role of geological structures on water leakage from karst dam sites in Zagros Region, Iran

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Abstract
In the Zagros Region, alternative karst and non-karst formations have been folded into a series of cylindrical synclines and anticlines. Some of folds are dissected by rivers oriented approximately perpendicular to the axes, forming excellent deep valleys for dam construction. Due to an ineffective site detection and inappropriate design and construction of grout curtain, some of the dams constructed on the folds in Zagros are facing with leakage problem or have been remediated. At this research, six schematic models for probable leakage route from the reservoirs constructed in synclines and anticlines are presented by considering fold characters and dam location. Results show that in synclines, the most important leakage controlling factors are thickness and permeability of the non-karst formations located at the floor or/and abutments of the reservoir. In case of anticlines, hydraulic relation between the limbs is the most important controlling factor. It was concluded that the precise problem appears at dam sites in which the anticline limbs are hydraulically connected and karst rocks are directly exposed on the surface or covered by a thin layer of permeable sediments at the floor or abutments of the reservoir. This kind of geological setting involves a high risk of leakage problem and reservoir needs an extended water-tightening system.

Keywords: Karst Dam Sites, Grout Curtain, Water Leakage, Folding, Zagros Region.

Introduction

The design and construction of dams and reservoirs in karst is a time and cost consuming task (Charlton et al., 2010; Milanovic, 2018). By rising of reservoir water, the surrounding groundwater level would be increased and water may leak to the downstream area through the dam foundation or abutments (Omofunmi et al., 2017; Mozafari et al., 2021). In order to prevent water leakage, construction of grout curtain and cut-off walls are common at any dam site (Filz & Bruce, 2017). Due to the complex hydrogeology, leakage possibility is higher in karst sites and therefore construction of water tightening system is usually more difficult, longer and expensive than other geological settings (Mozafari et al., 2021). Many dams have been built in the karst regions throughout the World, most of them have performed successfully, but failures in several projects has introduced karst as a dangerous environment for dam construction (Milanovic, 2004).

Iran in general has an arid or semi-arid climate with about 240 mm average annual precipitation. The major exceptions are the highest Zagros and Alborz mountains with at least 500 mm average annual precipitation (Babaeian et al., 2015; Mozafari et al., 2022). The raining usually occurs between Octobers to March, intensifies the water shortage in the remainder of year. In Iran, rivers are mostly originate from the Zagros and Alborz mountains, characterized by seasonal variations in flow. In some places, the main part of the entire year's rainfall occur

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in a few days, causing floods and local damage (Prospero et al., 2002; Raziei, 2018). The runoffs are so rapid that they cannot be used for agricultural purposes. As a semi-arid country and due to scarce water resources, to make use of the limited amounts of water, Iranian found the dam construction as a crucial element for providing drinking and irrigation water during last decades (Balali et al., 2009; Yazdandoost, 2016). Recently, many large and small dams with more than 30 billion cubic meters capacity are constructed in Iran in which most of them are located on karst foundations. Leakage problem has reduced reservoir storage and caused economic loss in several dams (Mozafari, 2015). The purpose of this study is to determine the role of geological structures on leakage from the karstic dam sites in Zagros Region. Results could be helpful in future grout curtain and dam constructions in Iran.

Geology

The Zagros, as a major structural zone of the Alpine–Himalayan orogenic belt, is extended near 1800 km from northwest of Iran down to Hormuz Island at the southeast (Fig. 1). To the northwest margin, the Zagros Zone is bounded by the Main Zagros Thrust Fault, approximate the suture zone between the Arabian and Iran plates (Agard et al., 2011; Ballato et al., 2011; Saein 2018). The Zagros Zone is characterized by 10-12 km thick successions of marine limestones, dolomites, siltstones, shales and salts which were deposited from Paleozoic to Pleistocene. Here, the main geological units in decreasing order of age include (Alavi, 2004): Hormoz evaporates (Eo-Cambrian); Paleozoic sandstone, shale and carbonates; Khami Group carbonates and shale (Jurassic-Lower Cretaceous); Bangestan Group carbonates and marlstone (Albian-Campanian); Pabdeh-Gurpi marlstone and shale (Upper Cretaceous); Asmari karst limestone (Oligo-Miocene); Fars Group evaporates, sandstone and Shale (middle to late Miocene); Bakhtiari conglomerate (Pliocene to Pleistocene); and Quaternary alluviums. Due to generated compressional stresses in the lithosphere by convergence between the Iran and Arabian plates from Triassic to Miocene, frequent large and small scale thrusting and folding (with northwest to southeast trending) were induced in these shelf sediments. Morphologically, Zagros is divided by the High Zagros Fault into the Crush subzone to the northeast and the Simply Folded subzone to the southwest (Fig. 1). The High Zagros is an intensively faulted and crushed subzone, thrusted onto the Simply Folded subzone, where the a series of huge northwest to southeast parallel anticlines and synclines have created an outstanding high lands that rise between 3000 to 3650 m asl (Mohajjel et al., 2003; Agard et al., 2005; Mouthereau et al., 2006; Ramsey et al., 2008). Similar to the other folded areas, anticlines and synclines in the Zagros Region are commonly affected by two frequent alignments of joints and faults, longitudinal and transverse (i.e. cross and diagonal faults) to the fold axis (Fig. 2). The longitudinal faults are roughly parallel to the fold axis and often fan around the fold. Cross faults are almost vertical to the fold axis, while the diagonal or strike slip faults generally occur in paired, conjugate sets oblique to the fold axis (Twiss & Moores, 1992; Cooper et al., 2006; Mercuri et al., 2021).

Material and Methods

From the lithological point of view, all the formations in Zagros Region are classified into non-karst and karst. The Hormoz Series, Kazhdumi, Pabdeh-Gurpi, Razak, and Fars Group are the main non-karst formations, while the carbonate parts of Khami and Bangestan groups (particularly the Surmah and Sarvak) and Asmari Formation are the main karst. About 23% of the region is covered by karst rocks.

At the Zagros, the alternative karst and non-karst formations have been folded into a series of northwest to southeast trending arch-shaped cylindrical folds. At the top of anticlines, the overlain weaker non-karst rocks (such as the siltstones and mudstones) have been removed by subsequent differential erosion and the more resistant karst rocks are now exposed. Here, the karst formations are usually sandwiched between the impermeable non-karst formations, make the considerable karst aquifers. The main recharge source of these aquifers is direct rainfall on the karst rocks. After infiltration, the flow direction is initially along the bedding plane and then parallel to the strike at the foot of the limbs, where it recharge the adjacent alluvium or discharge as springs.

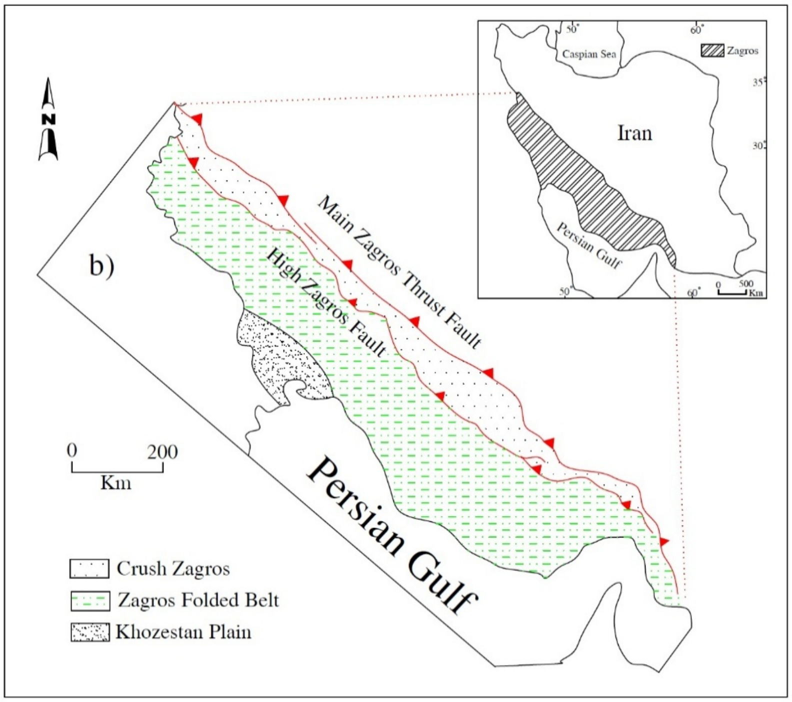

Figure 1. Major structural zones of Zagros, SW Iran (Adapted from Motiei 1993)

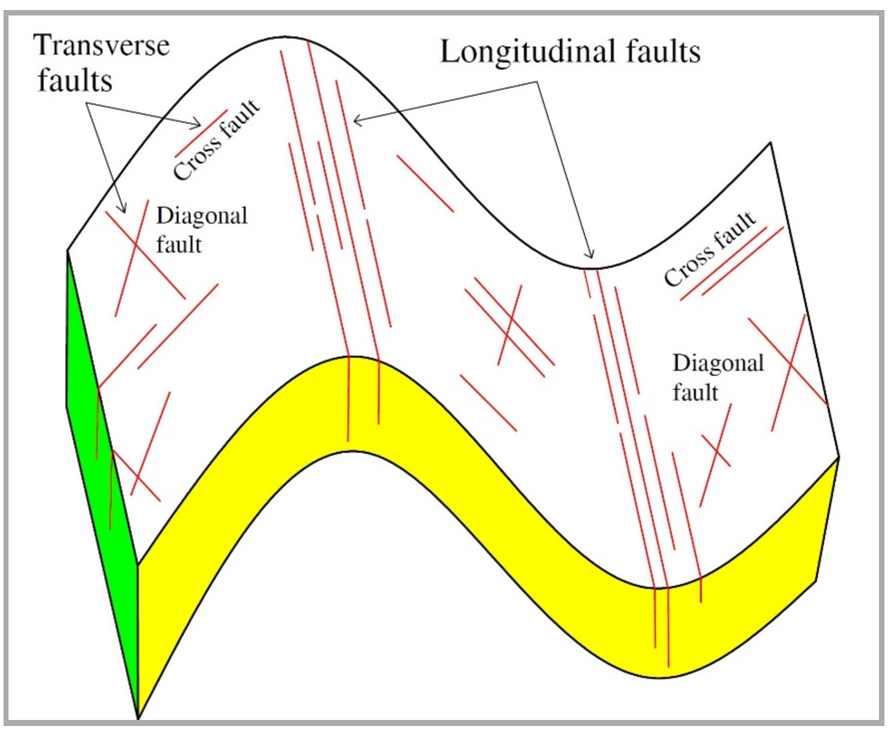

Figure 2. The major fault sets associated with anticlines and synclines

The Zagros Mountains are dissected by a series rivers that rise near its northeast margin and flow out to the Persian Gulf (Fig. 1). Some of the folds are crossed by rivers oriented nearly perpendicular to the fold axes, forming deep river valleys with near vertical walls (Oberlander, 1965), which have formed excellent topographic and geological settings for dam construction. More than 400 small and large dams (Such as Mirzaye Shirazi, Tange Sorkh, Dez, Gotvand, Semirom, Seymareh, Shahghasem, Karun I, Karun II, karun IV, Doroudzan, Sivand, Molasdra, Tangab, Delvari, Chamshir, Minab, Kowsar, Mrun, Karkheh, Shian, and Khasuyeh) are constructed in Zagros Zone, most of them located on karst formations. Most of these dams has negligible leakage, but a few have faced with considerable leakage. The dams are constructed on the upstream or downstream limb of the synclines or anticlines. At this research, six schematic models for probable leakage route from the reservoirs constructed in synclines and anticlines are presented by considering geological structures and dam location.

Discussion

The dams and reservoirs are constructed through a syncline or on an anticline. There are different hydrogeological settings and leakage conditions at each situation. Synclines usually formed valleys, surrounded by high ridges, topographically suitable for reservoir construction where a river is flowing through it. In a syncline, karst formations are preserved at both the limbs and in the core of the fold, extended along the fold axis to the plunges area. Therefore, in places where a reservoir is located inside a syncline, leakage can be occurred along the fold axis, in the dam foundation through the bedding planes or longitudinal faults, and at the abutments through the bedding planes or transverse faults. In this case, the depth and thickness of the karst formation, depth of karst, and lithology and thickness of the underlain and overlain formations are the main controlling factors of leakage. Generally, two following models could be expected for leakage from reservoirs constructed in a syncline:

Model A (Fig. 3): In places where the karst formations are located in depth below a thick impermeable formation, deep and extensive karst development is not probable and leakage is expected to be limited. Here, leakage could be occurred through the elevated karst formation at the abutments toward the plunges. The transverse faults may play a significant role in reservoir water transfer into karst. As an example, Mirzaye-Shirazi Dam is under construction in a syncline at the southeast of Zagros, where the reservoir bottom is sealed by the impermeable shale and marlstone of Pabdeh-Gurpi Formation. The Asmari Formation makes the elevated parts of the abutments. Based on the presented model, leakage problem from this reservoir would be occurred only through the elevated Asmari Formation at the both abutments toward downstream, particularly where the transverse faults are developed.

Model B (Fig. 4): Where the karst formations are exposed on the surface or burned under the permeable sediments or a thin impermeable formation, dam construction needs more attention. Such situation presents the most unsuitable conditions with respect to water-tightness, since deep karst has been developed along the bedding planes and longitudinal and transverse faults by action of the river during time. Depending on the position of the base level of erosion in the anticline and fault characters, karst could be developed hundreds of meters below the valley bottom and deep groundwater can be observed. Therefore, deep and expensive grouting treatment and filling of empty caverns are to be expected. Generally, these hydrogeological situations should be avoided for reservoir construction. The Tange-Sorkh Dam is under construction inside a syncline at the southeast of Zagros, where the reservoir area is composed of alternative layers of 1 to 3 m thick gypsum and 4 to 45 m thick marlstone layers (belong to the Razak Formation). A few small sinkholes and big cavities were observed in gypsum layers at the dam site. Therefore, leakage could be occurred through the gypsum layer at the syncline core and limbs after reservoir filling.

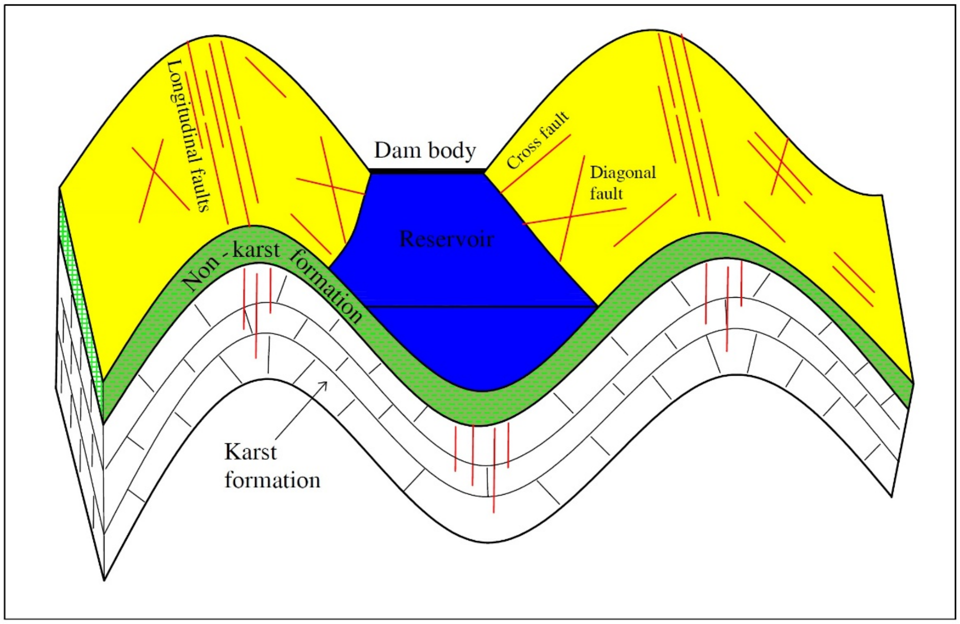

Figure 3. Model A: the dam and reservoir are constructed in a syncline, where the karst formation is located in depth below a thick impermeable formation

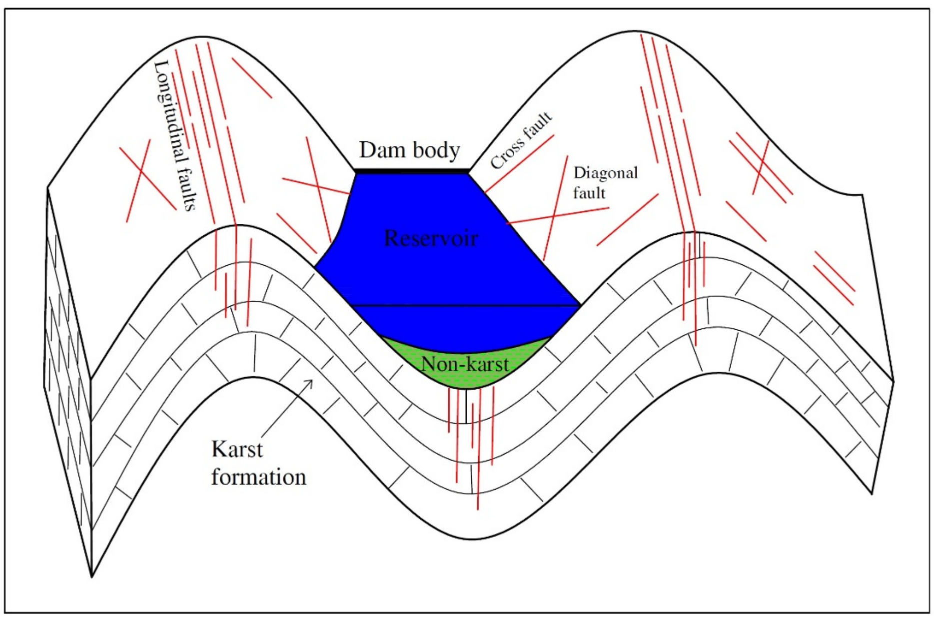

Figure 4. Model B: the dam and reservoir are constructed in a syncline, where the karst formation is directly exposed or covered by the permeable sediments

At the some sites, dams are located on the upstream limb of the anticline and the reservoirs are formed inside the adjacent syncline. Here, depending on the top elevation of impermeable non-karst formation in the core of anticline, two different leakage models would be expected.

Model C (Fig. 5): Where the top elevation of the non-karst formation is higher than the reservoir water level and consequently hydraulic relation between the upstream and downstream limbs of the anticline is impossible. Therefore, the reservoir water can infiltrate into the karst at the upstream limb and flow toward the new or pre-existing springs at the traversing river, fold plunges or a combination.

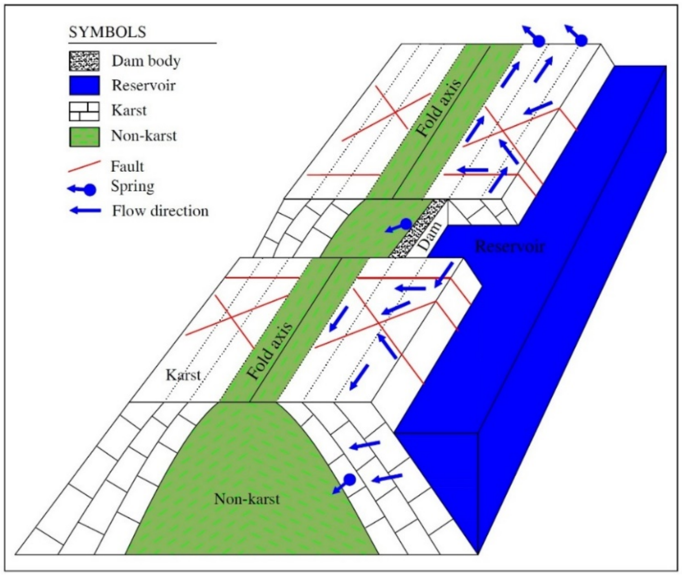

Figure 5. Model C: the dam is constructed on the upstream limb, where the impermeable non-karst formation is elevated in the core of the anticline

The Transverse faults and the bedding planes make the preferred routes for water transfer. To prevent leakage, grout curtain must be tight into the underlain and overlain impermeable formations at the bottom and ends. The Salman Farsi and Marun dams are constructed on the karst Asmari Formation at the upstream limb of the anticlines. The underlain Pabdeh-Gurpi Formation in the core of the anticlines is elevated higher than the reservoir water level at both dam sites. The as-built grout curtains through the karst formation at these dam sites work successfully since they were tight to the underlain and overlain impermeable formations.

Model D (Fig. 6): Where the underlain impermeable non-karst formation in the core of anticline is lower than the reservoir water level or even the riverbed, therefore the anticline limbs are hydraulically connected. After infiltration into the karst, reservoir water could be flow through the longitudinal and transverse faults together with the bedding planes toward the new or pre-existing springs located at the traversing river banks, foot of the downstream limb, fold plunges or a combination. To reduce leakage, grout curtain must be tight into the underlain and overlain impermeable formations at the bottom and ends. In sites where the executed grout curtain is hanging due to deep karst or extended distance to non-karst rocks, reservoir water could be leaked by passing the end or below the grout curtain even by its good performance. The Kowsar, Tangab and Seymareh dams are located at this kind of geological setting. At the three sites, reservoir water was emerged through the springs located on the downstream limb of corresponding anticline despite the extended as-built grout curtains.

At several sites, dam body is located on the downstream limb and the reservoir is formed inside the traversing valley throughout the anticline. While the reservoir water is in direct contact with the karst and could be leaked through the both limbs regardless of hydraulic relation between them, but two different leakage models could be presented depends on the elevation of non karst formation in the anticline core.

Model E (Fig. 7) where no hydraulic relation existed between the limbs due to elevated non-karst formation. Here, water has significant potential to flow through the transverse faults and bedding planes toward the new or pre-existing springs at the traversing river banks, plunges, or a combination. The proposed leakage paths could be blocked by extension of the grout curtain (in depth and at the ends) toward the underlain impermeable formation in the core of the anticline. The Karun I, Karun III and Karun IV are constructed on the Asmari Formation in this kind of geological setting. Leakage was negligible at these dam sites due to extension of the as-built grout curtain toward the underlain impermeable Pabdeh-Gurpi Formation at the bottom and ends.

Model F (Fig. 8): where the limbs are hydraulically connected since the non-karst formation is lower than the reservoir water level in the core of the anticline. Assuming a reservoir in this situation, water would be in direct contact with the karst formation throughout the valley, prepare an extended potential leakage zone. Water could be injected into the karst everywhere in the valley walls and flow toward the potential discharge zones all around the anticline. This kind of geological setting involves a high risk of leakage problem and reservoir needs an extended water-tightening system.

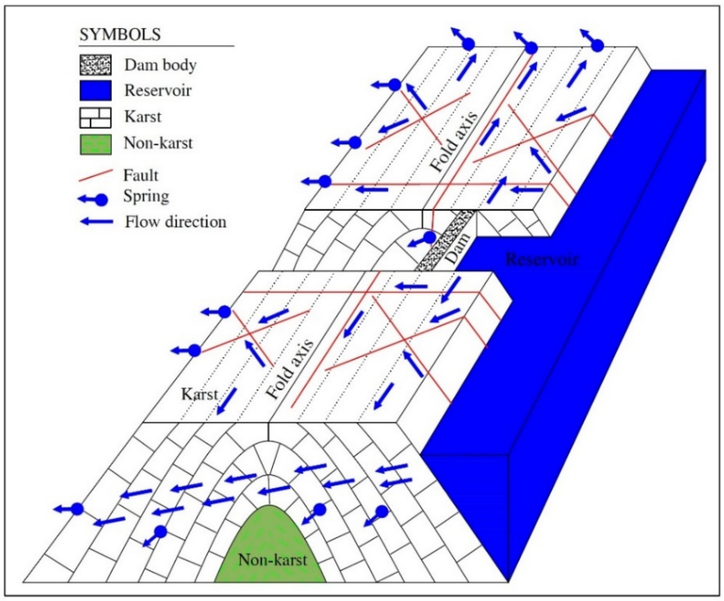

Figure 6. Model D: the dam is constructed on the upstream limb, where the impermeable non-karst formation is down in the core of the anticline

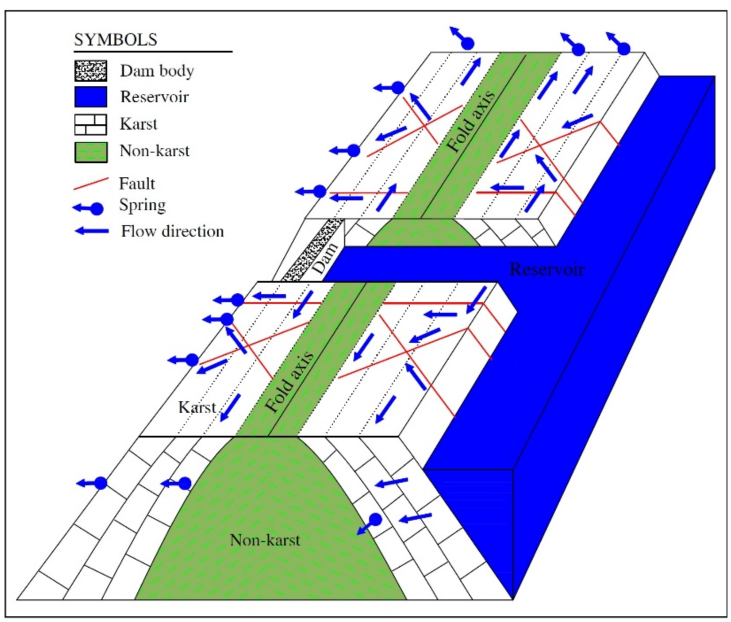

Figure 7. Model E: the dam is constructed on the downstream limb, where the impermeable non-karst formation is elevated in the core of the anticline

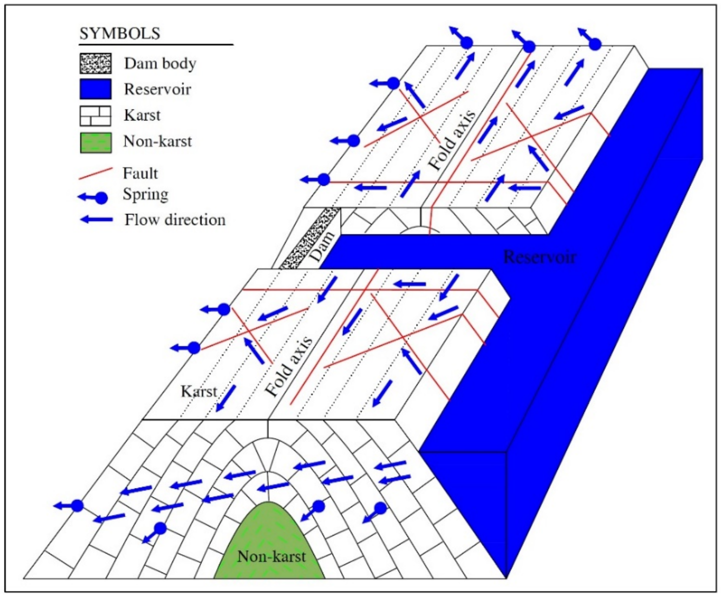

Figure 8. Model F: the dam is constructed on the downstream limb, where the impermeable non-karst formation is down in the core of the anticline

For example, the Shah-Ghasem Dam is constructed on the downstream limb of the Asmari Formation where the impermeable Pabdeh-Gurpi Formation is located in depth at the anticline core. After reservoir filling, huge leakage occurred toward downstream limb.

Conclusion

The main effective parameters on leakage from karst dam sites includes: insufficient geologic and hydrogeological investigation and explorations prior to dam construction; deep karst or paleo-karst; inadequate foundation preparation; internal erosion of the cavity infilling materials; inappropriate design and execution of grout curtain (hanging grout curtain, inadequate extension of grout curtain, single row grouting with entirely vertical holes, and inadequate injection and inappropriate composition of grouting mix). To design grout curtain, each site has to be evaluated based on the particular geological setting.

Most of the dams in Zagros Region are constructed on the folds, where the karst rocks formed a suitable valley for dam construction. The dam construction could be successful if a thick impermeable formation covers the karst rocks at the reservoir bottom and abutments in syncline, or there was no hydraulic relation between the anticline limbs due to elevated impermeable formation in the core of fold. To prevent leakage at these sites, grout curtain must be extended into the underlain and overlain impermeable formations at the bottom and ends. The particular problem appears when the karst rock is exposed or covered by a thin layer of sediments at the floor or abutments of the reservoir in syncline or where the anticline limbs are hydraulically connected due to deep impermeable formation in the core of fold. In these situations, the design and building of grout curtain are very complex and usually encounter significant problems. The uncertainties in these settings could be reduced prior to dam building by serious study of regional and local geological settings and hydrogeological condition (general and local groundwater regime, water balance calculation, tracing tests, and application of rock permeability tests).

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