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ORIGINAL ARTICLE

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Construction of grout curtain in karstic environment case study: Salman Farsi Dam

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Abstract Salman Farsi is an arch-gravity dam. It is 125 m high and located on the Ghareh-Agaj River in Fars province, south of Iran. From the geological and hydrogeological point of view, this dam is one of the most complicated sites in Iran. Existence of 40 springs at the river level (including hot springs), and many faults and crushed zones are part of these complications. The dam site is famous for its numerous big caverns. Main characteristics of the rock mass are: (1) low permeable limestone of moderate to high strength, (2) high karstification generally localized around intersection of faults or discontinuities. The main purpose of grout curtains is to change the hydrogeological characteristics (reducing the permeability) of the rock mass. Constructing a grout curtain in a karstic environment with a high random distribution of karst features contains some uncertainties and surprises cannot be excluded.During the excavation of grouting galleries, some big caverns at both abutments were discovered. The volume of the biggest one (Golshan's Cave) exceeds 150,000 m^3. A large-scale underground geotechnical treatment is needed to improve the water tightness of the dam site.

Keywords Grouting · Curtain · Gallery · Dam construction · Iran

Dam site geology

The dam body and grout curtain are on the Asmari Formation limestone. The Asmari Formation is divided to three units: Upper, Middle and Lower Asmari (Fig. 1). This formation belongs to the Oligomiocene period.

The Upper Asmari outcrops immediately from the upstream of the dam body. This unit is composed of shelly limestone, marl and marly limestone.

The Middle Asmari is composed of limestone, calcarenite, cherty limestone, nomolitic and oolitic limestone. The dam and most parts of the curtain are situated on this member. Due to its lithology, the karst features (channels, big caverns, chimneys, etc.) have developed in the Middle Asmari.

The Lower Asmari is downstream from the dam site. It contains regularly bedded limestone alternating with marls at the top and thin to very thin limestone and marly layers at the bottom. The lateral part of the grout curtain is constructed in the Lower Asmari.

Pabdeh Formation is downstream of the Lower Asmari. It consists of marly limestone, shale and marl. The shale and marl deposits make this formation impermeable. Its position (in the core of the Changal anticline) is key for dam site water tightness (Fig. 2).

The Changal anticline (Fig. 2) is the most important structure with regard to tectonic and hydrogeological conditions at the dam site. It is an asymmetric folded structure. Its plane strikes generally WNW–ESE and plunges steeply northwards. The core of the anticline consists of the Pabde Formation, an impervious

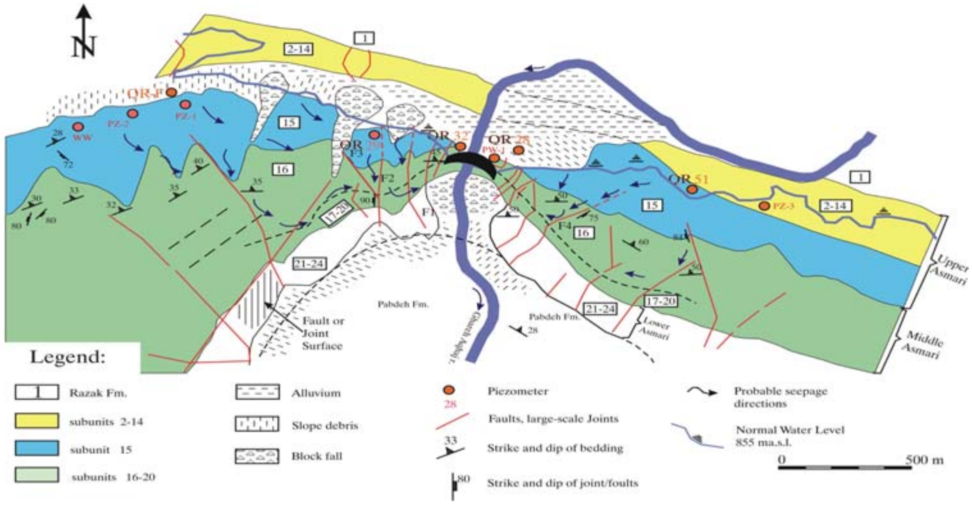

Fig. 1 Geological sketch of dam area

formation of marly limestone, shale and marl. The dam site is in the northern flank of the Changal anticline. During the folding process, the Changal anticline was disturbed by some fractures, faults and joint sets. Five joint sets are distinguished at the dam site. From the

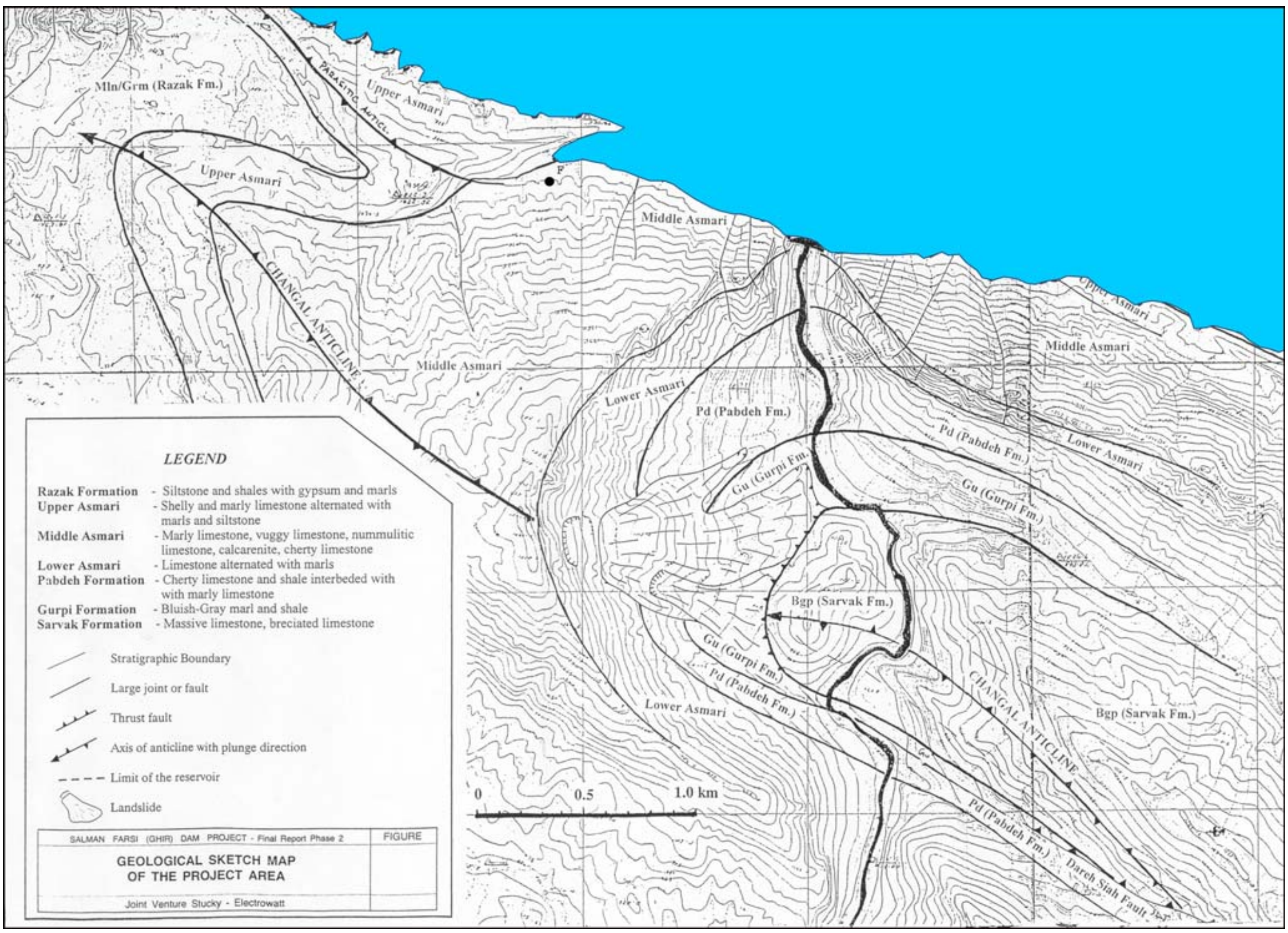

Fig. 2 Dam site area—Changal Anticline and position of Pabdeh Formation in its core

water tightness point of view two are very important, J1 (with the strike of NE–SW) and J2 (with the strike of N–S). Both sets are sub-vertical (dip about 80°). The bedding planes dip is 50–60° toward upstream.

Hydrogeology

With some marly layers, the Upper and Lower Asmari have low permeability. The Middle Asmari has much more limestone layers, and also the purity of the limestone increases. Limestone is very brittle, so during the folding process more fractures were developed in this unit. Well-developed J1 and J2 sets together with steep joints and bedding planes make a well-connected network for water filtration. The sub-vertical dip favors the groundwater circulation by gravity, provoking the karstification process. During the study phases, some springs (freatic water as well as artesian hot water) were detected along the river.

The Changal anticline has a key role in dam site hydrogeology. The Pabdeh Formation is in the core of the anticline. This formation, together with the bottom part of the Lower Asmari, acts as a thick and deep impervious barrier against underground water filtration from the upper erosion base levels to the lower levels. All springs (including thermal water springs) are upstream from Pabdeh. In other words, the hydrogeological connection between upstream and downstream parts of Pabdeh formation is cut. This is the key for designing and extending the grout curtain toward downstream. The karst aquifer was in constant adjustment to the level of the gorge bottom. During the fluvial modeling of the relief, the bottom of the gorge was cut by a very fast fluvial process. The discharge zone became progressively lower and the hydraulic gradients toward the gorge bottom were increased. The rock mass is fully exposed to the karstification process. This process could only develop down to the bottom of the gorge (Stucky-Electrowatt joint venture, 1996–2004: Salman Farsi Dam—mission reports).

It is assumed that the karst conducts exist down to the bottom of gorge level and this is the base level of karst. However, deeper karstification may be expected because of hot water upward flows. Two different types of karst can be seen: (1) Vuggy porosity and (2) Classical karst porosity. Vuggy porosity is mostly along layers, but vugs can also be found in scatter patterns. The diameter of vugs ranges between a few millimeters to 20 cm. The hydrogeological role of vuggy porosity is secondary. Classical karst porosity can be seen in forms of chimneys, sub-horizontal and sub-vertical channels, caverns and big caves. The karst is formed along faults or main discontinuities. Parts of the caverns have filled with well-stratified, compressed and plastic clays. Karst features are usually poor with speleothems and very dry. Permanent or temporary water does not exist above river elevation.

Grout curtain

General design criteria for Salman Farsi Dam are listed below.

Acceptable water tightness: the main purpose of the project is downstream irrigation. It is not necessary to

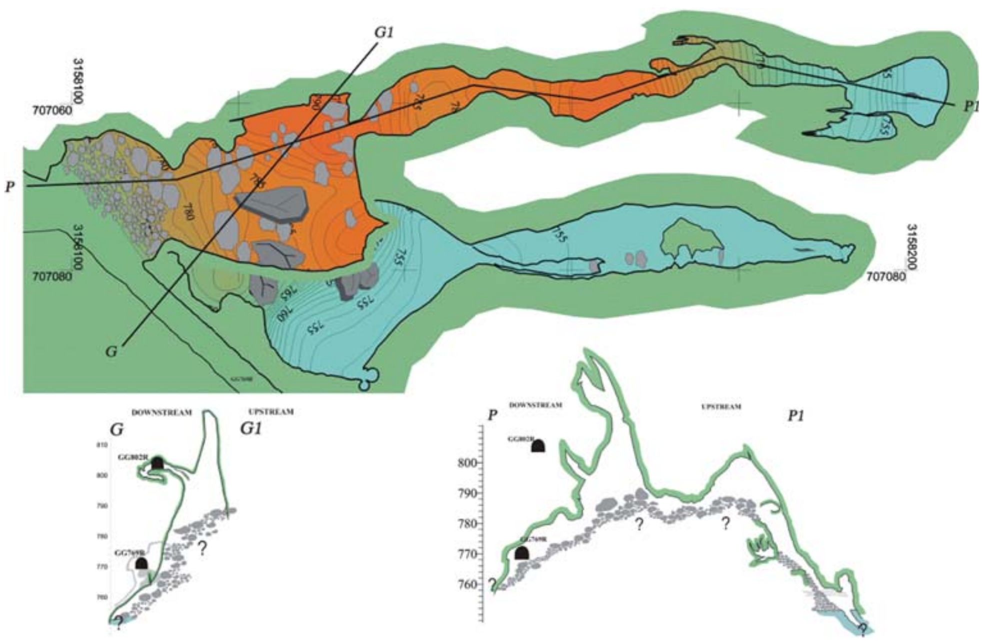

Fig. 3 Plan and cross-sections of Golshan Cave (from Vuckovic and Milanovic 2001)

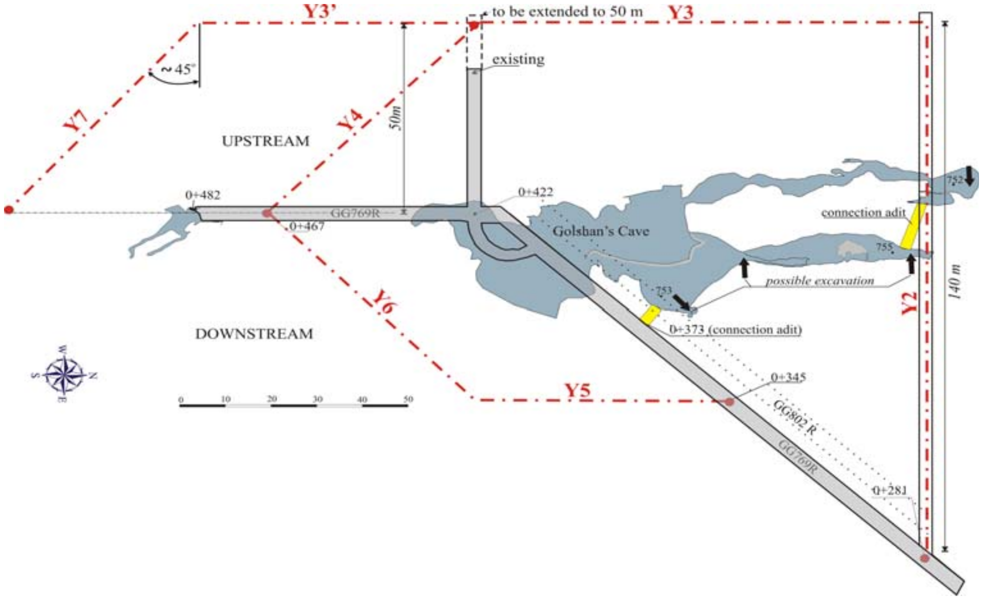

Fig. 4 Grout curtain bypasses the Golshan's Cave (from Stucky-Electrowatt 1996–2004)

achieve a perfectly impermeable curtain. The leaked water will return to the river. The main criterion is to avoid progressive erosion.

Sufficient lateral extension: to avoid downstream bypass of the curtain, the lateral part of the curtain should be in an impermeable rock.

Depth below dam body: it is important to be conservative in the depth of the curtain below the dam body. The designed depth for this purpose is 140 m below the dam body.

Detection of karst: the curtain must detect all the karst channels. In order to achieve this criteria:

Table 1 Advantages and disadvantages of proposed solutions (Stucky-Electrowatt joint venture, 1996–2004: Salman Farsi Dam—mission reports)

Option 1	Cutoff through existing geometry of grout curtain
Approach	The curtain geometry will not be changed, which means the curtain goes through Golshan's cave. This means treatment of the cave area. This treatment contains several structural measures, such as a cut-off wall within the cave (gravity-type wall), plugging and filling of chimneys and smaller cavities and subsequent contact and curtain grouting. The main impediment is the blocky material in the cave which impairs judgment of the foundation below it.
Advantage	No diversion from existing geometry.
Disadvantages	A complicated large and expensive structure would be exposed to full hydrostatic head. Foundation of gravity wall in Golshan's cave would need full excavation of blocky material or reliable treatment to obtain an acceptable foundation base. There is risk of impact forces of unstable rock on gravity wall during earthquakes and transient water table conditions during reservoir operation. Because of all the above, this is hardly considered as a feasible option.
Option 2	Upstream bypass of Golshan's Cave.
Approach	The grout curtain will be oriented locally upstream of Golshan's cave to leave it downstream of the curtain alignment. Two options are tentatively under discussion.
Advantages	No or only little treatment of the cave area would be needed, i.e., large cut-off measures are avoided. There is automatic intersection of northwards oriented channels, such as Fazeli and Parhizkari's channels. Less karstified rock mass is likely along the bedding planes at a further distance from the river. Golshan's cave is left dry.
Disadvantages	Drastic change of geometry as all grout galleries have to be shifted upstream by about 100 m. Longer grout curtain galleries and larger surface than options 1 and 3. Further investigations are necessary. High hydraulic gradient would occur between curtain plane and cave.
Option 3	Downstream bypass of Golshan's cave.
Approach	The grout curtain will be oriented locally downstream of the cave, leaving the entire karst area upstream of the curtain. This option comprises separate treatment of incidence along Fazeli's and Parhizkari's channels.
Advantages	No or only little treatment of the cave area is required, i.e., large cutoff measures are avoided. There is less deviation from existing curtain geometry than option 2. Fewer quantities of materials are involved.
Disadvantages	The alignment of karst channels both towards south and the river are unknown. Further investigations are necessary. Separate treatment of northwards oriented channels is required. High hydrostatic pressure is exerted on the grout curtain due to closeness to Golshan's cave.

1. The grouting galleries are designed vertically close to each other (average 30 m)
2. Extensive investigation was performed earlier (and still is continuing during the construction phase), including: exploratory drilling, adits and speleological works.
3. Orientation of galleries is designed to intersect major karst features.

Intersection of joint sets: the orientation of boreholes has to intersect bedding planes and main joint sets (J1 and J2). Satisfactory performance after impounding should be achieved.

Resistance against aggressive water: portland cement (types II) was selected to resist against sulfide (SO_4 ion).

Geometry of the curtain

As it was mentioned, the geometry of curtain is based on reaching the impermeable layers (Pabde and base part of Lower Asmari) downstream of the dam body. During the excavation of grouting galleries, some big caverns at both abutments were discovered. The volume of the biggest one (Golshan's Cave) exceeds 150,000 m^3 (Fig. 3). This cave is at the right abutment. A variety of karst features with different volumes observes in the cave. The bottom of the cave is covered by clay materials or by some big blocks and the elevation of sound rock is not known. There are two long, faulty karstic channels. They cut the curtain in a north–south direction. The designed curtain should pass through the cave. There were some significant problems with this cave:

1. Constructing a successful grout curtain was quite doubtful due to its complication.
2. Walls of the cave were not sound. Technically, constructing a concrete structure through it did not seem promising.
3. Considering the volume of the cave, it was not economical to fill it with concrete.

To solve the problem, a Value Engineering Seminar was held. In this seminar three different solutions (Fig. 4) were discussed and an economical estimation for each option was calculated. Table 1 shows the advantages and disadvantages of each option.

After a long discussion, it was decided that upstream bypass of Golshan's cave is the best solution (Fig. 4). Four galleries (853R, 802R, 769R, 738R) were shifted upstream of the Golshan's cave and the grout curtain had an extension of 1,560 m. The karst treatment took about 1.5 years, but the final results seem satisfactory. The old route of the curtain will be used to monitor the curtain performance. The new curtain route is well known and has the least karst volume. The karst treatment was done and it took only 1,020 m^3 to fill the karst with concrete. The drilling and grouting works are being executed now.

Selecting the grout mix

Most parts of the curtain are in karstic limestone; so, water will reach the curtain via karst channels and exert full pressure on the curtain. This means that the curtain should have very good physical characteristics to resist water pressure.

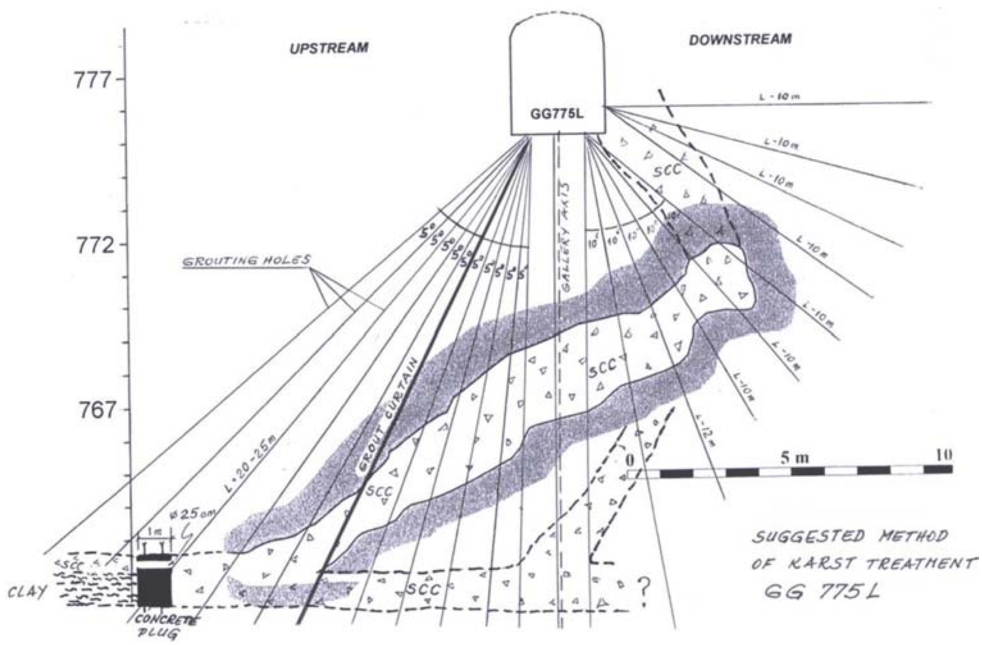

Fig. 5 Large cavern treatment (from Stucky-Electrowatt 1996–2000)

To achieve this goal, a thick grout mix with a water/cement ratio of W/C = 1/1 to W/C = 1/1.5 was used. This kind of grout mix is very suitable for Salman Fasi grout curtain. The main advantages are: (1) the curtain has a high strength against water; (2) the grout mix is stable and has a low percentage of bleeding; (3) all parts of the curtain have uniform characteristics so evaluation is easy.

Selecting the grouting pressure

The following points should be considered:

1. The rock mass has low permeability. This means that more energy is needed to push the grout along the half-closed discontinuities. The rock mass strength is high enough to use high pressure.
2. Filling all karst features around the curtain is a must. One of the main answers to this problem is increasing the penetrating radius of the grout.
3. The strength of the rock mass is moderate to high; it has good resistance against the pressure. Hydrofracturing is not likely to occur in this kind of rock mass. But if it occurs and the grout reaches a karst feature, it is welcomed. The above points call for a high pressure. A final pressure of 40 bars was used to solve the problem.

Additives

Thick grout mix has high viscosity and cohesion. Both these factors act against moving the grout along discontinuities. Super Plasticizer (1% of cement weight) was used to reduce viscosity and cohesion (or to increase the penetrating radius).

Large cavern treatment

The large cavern treatment is one of the most difficult underground works (Fig. 5). It consists of five different phases:

1. Determining the position: speleological maps were used for this purpose.
2. Removing and cleaning: this is the most difficult and time-consuming phase. It consists of removing all kinds of material (local fragments and blocks, crushed material, clay deposits and water) from the karst. Usually removing the materials and cleaning will continue until reaching sound rock. It often needs some extra shaft and adit excavation as well as blasting. Cavern treatment was performed 20 m upstream and 10 m downstream of the curtain. In Salman Farsi Dam, it took years to clean some big caverns.
3. Filling the caverns with concrete: if the cavern was accessible and it did not have a big volume, it was filled with concrete. When the cavern had a large volume, only a few meters upstream and downstream of the curtain were filled. This is called concrete plugging. If the cavern was accessible and it did not have a big volume, it was totally filled with concrete.
4. Contact grouting: after executing concrete plug, some contact grouting would be done to fill the empty spaces between concrete and rock.
5. Connection between concrete plug and curtain: after completing the above phases, more grouting holes were drilled to connect the curtain to the plug.

Conclusion

Construction of a grout curtain in a karstic environment needs precise investigations and is often expensive. Although the main purpose of these investigations is to determine the exact location of karst features; so far, there is not a single reliable method to achieve it (Milanović 2000: Geological engineering in Karst, Zebra Publishing, Belgrade). It was necessary to use a combination of different methods (e.g., drilling and grouting, monitoring, dye tests) to find possible leaking routes. Providing precise speleological maps is very important for cavern treatments. In a karstified rock mass, the curtain often needs adaptation and modification based on findings during grouting. The final design of the curtain can only be made during the execution phase. Modification is a rule, not an exception, and this lies in the nature of the karstic environment.

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