Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Jannah Dam in Lebanon – a remarkably broad range of applied geotechnical works

Mazin Adnan[1], Michael Baltruschat[2], Georges Abdo[3], Khalil Daher[4]

[1] BAUER Spezialtiefbau GmbH, Schrobenhausen, Germany, mazin.adnan@bauer.de
2 BAUER Spezialtiefbau GmbH, Schrobenhausen, Germany, michael.baltruschat@bauer.de
3 BAUER Lebanon Foundation Specialists. S.a.r.l., Beirut, Lebanon, georges.abdo@bauer.de
4 BAUER International FZE, Abu Dhabi, UAE, khalil.daher@bauer.de

Abstract. The Jannah Dam is designed as a massive arch-gravity dam with a height of 162 m above foundation. The dam is built in a steep valley with heterogeneous ground conditions: granular soils, boulders of limestone, basalt and chert, underlain by rock. The fresh rock - limestone and dolostone - has compressive strengths up to 60 MPa. Between 2017 and 2021, BAUER Lebanon executed various foundation works on site, including about 9.500 m² of plastic concrete Cut -off walls (CoW), at both cofferdams, extending over a length of 128 m (U/S) and 161 m (D/S), in addition to multiple rows of overlapping diaphragm walls (d-walls), as a bulkhead. This execution concept, proposed by Bauer instead of originally considered jet grouting block, supports the deep excavation to the foundation level of the dam. The arch-shaped d-walls, with a depth of 38 m at deepest excavation axis, totaling to 3.610 m², were constructed mostly in zones of noticeable permeability, which exacerbated the challenges imposed by the locally encountered artesian conditions. The three parallel walls, each with a wall thickness of 120 cm, are connected by a capping beam. A secant pile wall was used for subsoil improvement in the area of a geological fault. Grout curtains were constructed along the embankment foundation and in the abutments, whilst consolidation grouting of the rock was executed under the highly stressed parts of the foundation. The drilling depth reached about 94 m. Special rails have been installed on the slopes to allow safe and accurate drilling and grouting works on slopes fulfilling strict quality and safety requirements.

Keywords: Cut-off wall, diaphragm wall, bulkhead, grout curtain, secant pile wall, plastic concrete, GIN

1 Introduction

Please Although Lebanon is relatively generously endowed with water resources, such as river basins and a relatively large aquifer, the risk of acute water scarcity does still exist, mainly due to non-uniform distribution and seasonal variations in water resources. The lack of infrastructure to capture and use surface runoff, as well as the significant losses in the water distribution network greatly exacerbate the problem. The water shortage in the Mount Lebanon and Greater Beirut area in the year 2035 is estimated by the World Bank at more than 350 million cubic meters. Jannah Dam, with a design capacity of up note that the first paragraph of a section or subsection is not to 38 million cubic meters, along with other envisaged dams, is expected to help alleviate the problem of water scarcity. The planning study, as well as the dam design, was carried out by the engineering firm Khatib & Alami and the Artelia Group respectively. The construction was entrusted to Andrade Gutierrez Group, as the main contractor.

2. Soil conditions

The project site extends over a length of 500 m in a relatively narrow, steep and rocky section of the Jannah Valley. The soil conditions are characterized by Quaternary alluvial deposits with a thickness of up to 53 m and underlying limestone and dolomite (Fig. 1).

The alluvial deposits consist mainly of the following:

- Gravels, cobbles and blocks of limestone and dolomite in fine- to coarse-grained sandy-clayey matrix
- Medium-dense to dense, slightly loamy to clayey sand, partly with gravel inclusions. Intermittent areas of loosely bedded sand were also recorded
- Soft to very stiff clay with intercalated bands of sand

The underlying bedrock consists mainly of dolomite stone and is strongly to moderately fissured. Nests of completely weathered basalt, 10-20 m thick were detected as tuff within the dolomite formation. At depths of up to 50 meters, open caverns were found in several places during the soil investigation campaign. Several tectonic folds do exist adjacent to or across the project area.

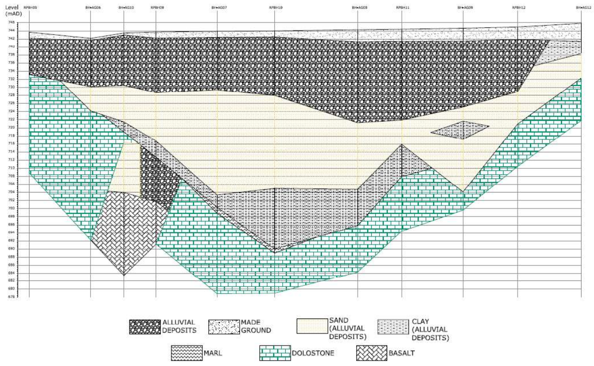


Fig. 1. Typical geotechnical section /1/

3. Scope of Work

The main geotechnical measures executed on this project included (Figures 2a & 2b):

- Cut-off wall at Upstream cofferdam
- Cut-off wall at Downstream cofferdam
- Diaphragm walls to create a bulkhead
- Consolidation and curtain grouting
- Ground improvement by means of piles

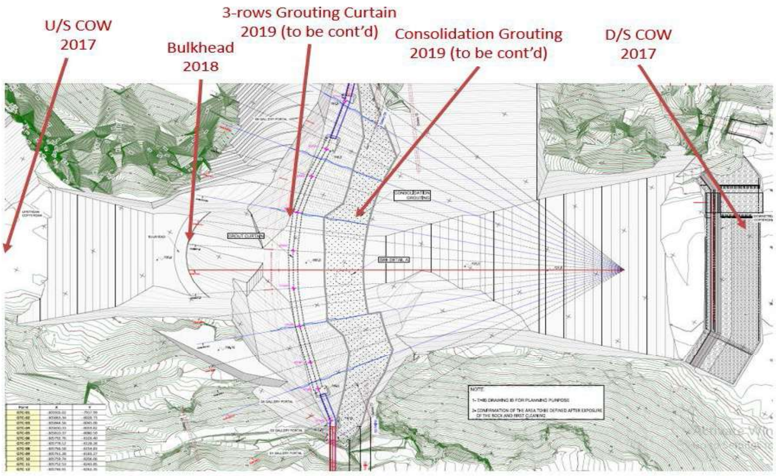


Fig. 2a. The foundation engineering measures executed - General layout

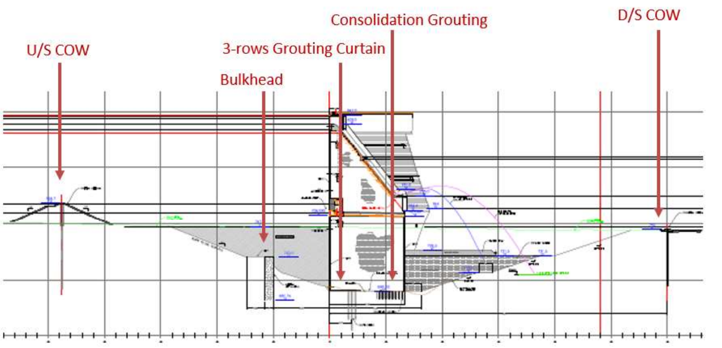


Fig. 2b. The foundation engineering measures executed - Cross-section

A major challenge of the project was the required deep excavation below the river level. Special concepts to control the water ingress and ensure the stability of the excavation and the footing had to be implemented.

4. Cut-off walls at cofferdams

The cut-off wall at the upstream cofferdam extended to a depth of 42 m and stretched to about 128 m (Fig. 3). The excavation was predominantly in alluvial deposits. On the slopes, the cut-off walls are keying into the bedrock. The cut-off wall at the downstream cofferdam extended over 161 m, and the maximum depth reached 50 m.
In view of the required depths in the heterogeneous subsoil and the requirements both to cut into the rock at greater depth and to key into the steep rock shoulders at the abutments, Bauer Spezialtiefbau proposed the utilization of the cutter technique. In addition to the reliable verticality control and higher performance, this technology mitigates the so-called hydraulic windows at the connection to the bedrock.

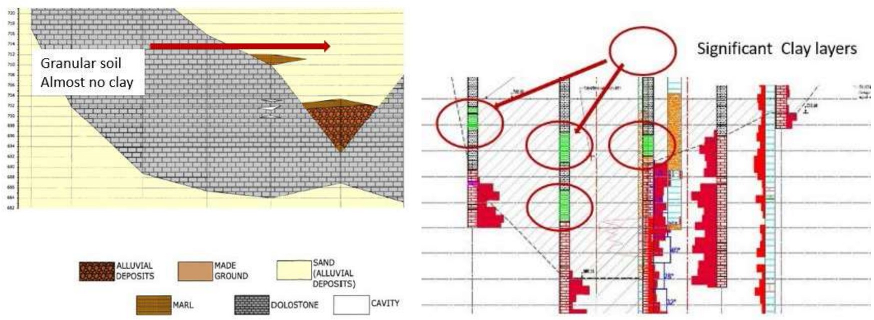
Fig. 3. Execution of cut-off wall at upstream cofferdam

5. Bulkhead - as a block of diaphragm walls

One of the remarkable challenges on this project was the execution of the bulkhead required for the excavation down to the foundation depth of the dam main body in the non-rocky soil. The relatively limited dimensions of the stretch available for the construction and the related hydraulic conditions prohibited an open excavation.

According to the original concept, the watertight bulkhead was supposed to be executed in about 35-m-thick alluvial deposits, classified as non-cohesive, with the jet-grouting technique. The arch-shaped bulkhead was designed with a thickness of 4 m, supported in the bottom part with tie-back rods. The compressive strength of the bulkhead was specified with 7 MPa, a fully realistic strength magnitude for jet grouting columns executed in non-cohesive soil layers. The Designer identified, however, the necessity to address, besides the compressive stresses in the arch-body, also the critical aspect of the shear at the base of the bulkhead.

In view of the sensitivity of the bulkhead stability issue, the Engineer has initiated an additional intensified soil investigation campaign, which revealed the existence of significant clay layers in the bulkhead axis (Fig. 4).



Originally expected soil conditions in the bulkhead axis

Actually encountered conditions upon intensification of reconnaissance bores

Fig. 4. Soil conditions in the bulkhead axis

The new information imposed a re-assessment of the technical feasibility and related cost and time implications for the application of the jet grouting technique. The substantial differences of the jet grouting body, when constructed in sandy soil compared to clayey soil, is related mainly to following factors:

- Smaller achieved diameters of the columns; whilst jet columns with 4.35 m diameter are well achievable in non-cohesive sand layers (Fig.5), the corresponding diameters in clayey soils are typically by far smaller (Fig. 6), due to the considerably higher resistance of the cohesive soil to erosion.

Fig. 5. Jet grout columns with 4.35 m diameter in clean sand

Fig. 6. Jet grout columns with 1.35 m diameter in clayey soil

The correlation between achievable diameters in sand and clay has been described, amongst others, by Flora [2] with the equations

$$D = D_{ref} \cdot \left(\frac{\alpha_E . \Lambda^* . E'_{\ n}}{7{,}5 \ . \ 10}\right)^{\beta} \cdot \left(\frac{N_{SPT}}{10}\right)^{\delta}$$

(for coarse grained soils, with E'_n in MJ/m)

and

$$D = D_{ref} \cdot \left(\frac{\alpha_E . \Lambda^* . E'_{\ n}}{7{,}5 \ . 10}\right)^{\beta} \cdot \left(\frac{q_c}{1.5}\right)^{\delta},$$

(for fine grained soils, E'_n in MJ/m and q_c in MPa)

where D_{ref} quantifies the role of grain size composition of the original soil, being equal to 0.5, 0.8 and 1.0 for respectively fine-grained soil, coarse-grained soil with and without a significant amount of fine material. It becomes evident, that under otherwise comparable conditions the diameter of a jet grout column in clay will not exceed 50% of the jet grout column in sand.

For the dimensioning, the least favourable soil layer should be targeted, if the aim is to create a quasi-monolithic, reliably interlocked block, since the diameters of the jet grouting columns do reflect the erodibility of the layers encountered over the treatment stretch, i.e. treatment height (Fig 7).

Fig. 7. Jet grout column produced in interbedded soil layers

- Denser grid to produce an interlocked body, resulting in higher number of columns and accordingly more linear meter; the block pattern, based upon the achievable column diameter and the hole deviation, had to be densified by 60-65% in the new conditions, significantly increasing the required number of columns and accordingly the linear meter of jet grouting to be executed. The reduction of the jet column diameter is additionally aggravated by the deviation consideration, since the design height of the bulkhead approaches 35 m.
- Lower production rate, due to much longer retrieval rates; the retrieval rate had to be increased from 6min/m to more than double of this value to achieve column diameters of practicable utilization rate. Using the available pressure capacities of the pump and the optimal revolution in all soil conditions, it is mainly the retrieval rate that remains as an instrument to achieve the larger column diameters in cohesive soils. Figure 8 below demonstrates the results of Bauer's experimental in-situ tests, showing the correlation retrieval rate versus diameter in similar soil conditions.

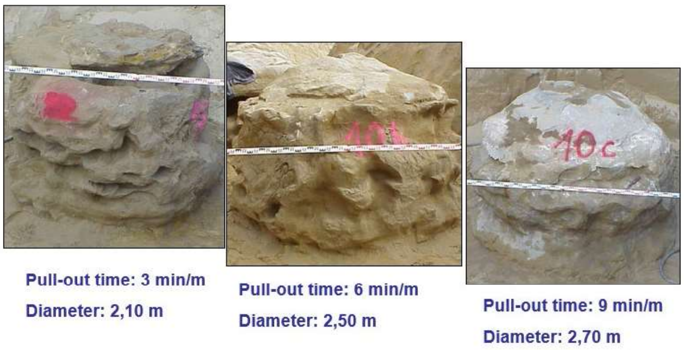


Fig. 8. Influence of retrieval rate on diameters achieved

- Higher cement consumption and larger quantities of return fluid to be disposed; the compressive strengths of the jet grouting bulkhead specified by the project are well controllable and achievable with moderate cement contents in sand. For the case of clayey soil however, the cement content must be remarkably increased to achieve the required strength level, due to the following factors:
    - The necessity to apply the triple-fluid system, where the fluid soil-water mix created by the jetting phase 1, has to be replaced by a cement-rich grout with a water-cement ratio not below 0.5, i.e. with a grout having a cement content of about 1200-1250 kg/m$^{3.}$

- The relatively high water content of the cohesive soil imposes much a higher cement content to achieve the required strength.
- Whilst the sandy soil can be utilized as a sort of aggregate, contributing to a certain extent to the compressive strength in the final jet grouting mix, the cohesive clayey soil must be almost completely replaced by the neat cement grout.

The consideration of a different version of the jet grouting technique, besides the much longer retrieval rate, associated with almost total replacement of eroded soil by a viscous and solid-rich grout filling, results in much higher quantities of back-flow sludge.

The updated profiles in the bulkhead section (Fig. 9) further allowed the conclusion that the portion and location of the soil zones with intermediate properties, between the pronounced cohesive and the non-cohesive soils, is variable even within a very limited distance.

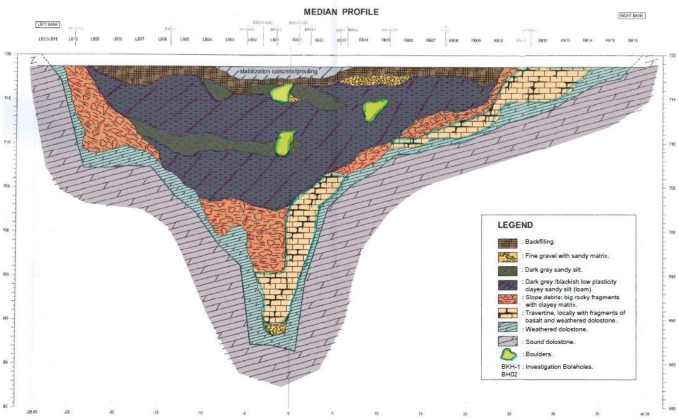


Fig. 9. Soil profile in the bulkhead section

The dimensioning of the column pattern to achieve full overlap everywhere, had to be conservative enough to prevent the occurrence of "gap-windows" in unsuitable soil layers. The prototypical figure 10 schematically illustrates the consequence of the implementation of optimistic execution parameters in soil layers with different properties. Further, the effect of boulders and blocks with the related "shade effect" must be conservatively assumed, requiring additional grid densification.

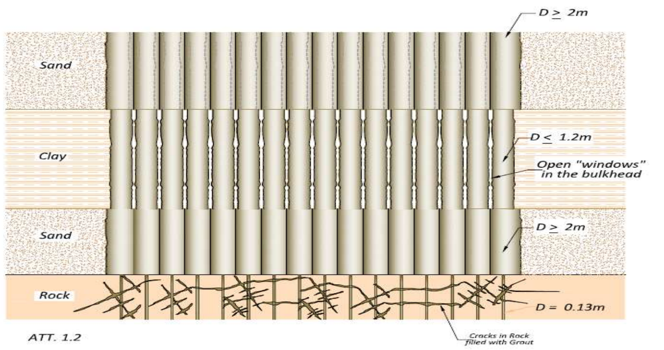


Fig. 10. Scheme of expected jet efficiency in multi-layered soil

For the reasons above, a need of an alternative, technically and economically more suitable solution was acknowledged. Bauer proposed the consideration of large soil replacement elements. The aspects and components defined in discussions with the Designer- Engineer being of crucial importance for the execution of the Bulkhead were summarized with:

- Possibly large, massive, elements
- Reliable achievement of design properties, despite the random and stochastic nature of valley deposits, with respect to dimensions and geometry of elements, the compressive and shear strengths, as well as the permeability
- The practicability of execution to design depths, in addition to the feasibility of reliable embedment into the bedrock
- Reliably controllable deviations and overlap between the elements without significant untreated soil gaps, as well as a reliable interlocking to achieve required system permeability
- The possibility to introduce reinforcement, if considered advantageous for optimized dimensioning of the bulkhead thickness
- Cost optimization and respecting the scheduled timeframe for the execution

The comparison between the relevant aspects of circular versus rectangular elements are summarized with (table 1):

Table 1. Comparison between circular and rectangular elements

Requirement	**Circular Bores**	**Rectangular Barrettes**
Homogeneous block in all soil layers	+	+
Reliably interlocked block, maintaining integrity and interlocking despite movements during later excavation	+	++
Toe embedment in competent stratum	+	+
Water ingress Control	3 times larger joints area than with barrettes	Only 30% of the joint area of piles
Deviation limits correction	1.0% for deep part. Time consuming	0.3 % Simultaneous / convenient
Strength for compression-arch and shear at toe. Limitation due to overcutting ratio	Up to 10 MPa	> 25 Mpa
Reinforcement installation / feasibility	Only in 25% of piles	In 100% of barrettes
Keying into rock slope / outcrops	+	++
Costs compared to jet grouting in clay	+	++
Concrete overconsumption	High overcutting ratio	Low overcutting ratio

The very constructive and trustful relation to the Main Contractor and the Engineer allowed a productive discussion leading to substitution of the jet grouting block by overlapped barrettes Fig. 11. The Designer, being highly experienced in design of

arched gravity dams, avoided with his design geometry and shape the need for reinforcement.
The additional investigations to the hydrological conditions in the axis of the bulkhead further revealed the existence of artesian conditions in lower aquifer layers, overlain by clayey aquitard, which are of pronounced significance for the construction of the bulkhead, affecting the stability of open trenches (Fig.12).

The observation of the raising level of the support fluid within the guide-wall, associated by clear bubbling, so-called boiling, are a clear indicator for the

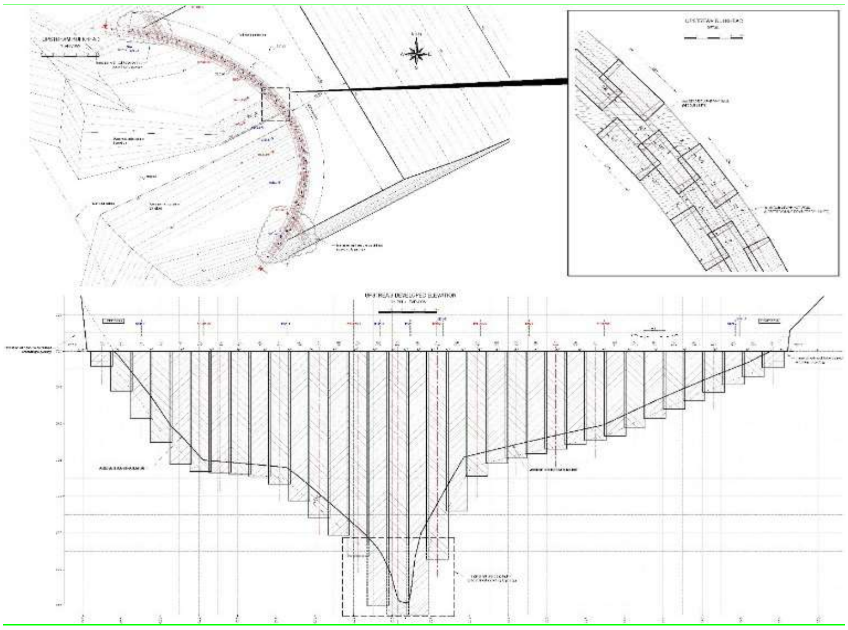


Fig. 11. Bulkhead executed as overlapped D-walls

insufficiently balanced hydraulic conditions, especially, upon slurry treatment and/or replacement prior to concreting, to meet the requirements of the EN 1538. This situation was addressed considering such measures as trench pre-treatment with cement slurry, installation of overflow water collection sums and, ballasting the supporting fluid with additional solids. As a modified base for the definition of slurry limits prior and during concreting the DIN 4126/1986 (clause 7.3) was adopted, which specifies maximum specific weight of the slurry prior to concreting based on buoyancy considerations preventing the so-called “sand rain” with its adverse effect on the quality of cast concrete. Those adjustments were accompanied by monitoring of possible slurry dilution, which would indicate an uncontrolled water ingress. Only upon such verification the concreting was allowed to start.

The construction of the diaphragm walls had to be associated with preliminary grouting measures. Some zones, with boulders and bedrock fragments adjacent to the trenches, had to be pre-treated to prevent them from falling onto the cutter during the excavation. On the other hand, the soil package confined by both outer rows did also require special attention. The statically required use of structural concrete presupposed that the cutting

of the already concreted panels was carried out as symmetrically as possible. For this reason, the two outer diaphragm wall rows were constructed first, followed by the middle row of the bulkhead structure. The coarse-grained soil between the two outer diaphragm wall rows therefore had to be pre-treated as well. Otherwise, during the construction of the second external row, the slurry would penetrate into this zone and lean against the previously produced first external row. The supporting effect would be lost, and the entire soil package located between the external rows could fall into the open trench. Apart from the acute risk for the cutter in the open panel, such a situation would require full-scale concrete cutting, together with the associated considerable wear and loss of performance.
A further challenge for the bulkhead execution was the extremely congested work area in the relatively narrow Jannah-valley Fig. 13.

Fig. 13. Imposed congested working zone with dumpers, access road to reservoir, stockpile area through the bulkhead working area

The exposed bulkhead was later inspected to detect any water ingress spots and cognizable joints between the separate panels. The exposed surface of the bulkhead delivered highly satisfactory appearance Fig. 14.

6. Grouting

The grouting works on the project consisted of consolidation grouting under the footprint of the dam and three rows of grouting curtains extended into the abutments through several layers of galleries (Fig. 14), with the related QA/QC measures, such as coring and water pressure tests. The maximum depth reached some 80 m in the foundation section and extended down to 100 m at the abutments.

Fig. 14. Mobile platforms for drilling and grouting works on slopes with the exposed bulkhead behind (left) and working in gallery (right)

The execution of grouting works under the base of the dam followed the excavation down to the surface of the rock under the protection of the bulkhead.

The execution of the works on the steep slopes with natural rock slopes in excess of 45° required special measures for the execution. Mobile platforms on rails with multiple redundant brake and fixation systems were developed, constructed, and erected for this project.

The trial grouting panels delivered data to the suitability and efficiency of the originally defined, GIN-based, grouting concept and procedure. The obtained results, compiling the execution parameters and the achieved efficiency of the test section of the grouting curtain, were evaluated by the Engineer and remaining involved parties and conclusions drawn for the execution of the main works. The applicability of the GIN method, without modifications considering the particular geological conditions of the rock stratum on Jannah Dam, was considered to be of limited suitability. The co-existence of cavities on one side and relatively tight joints in the rock stratum on the other side impaired the suitability of the GIN method on the given project. Possibly, the rock properties in the sense of the pattern of the discontinuities at the dam location, have been particularly affected by the tectonic movements manifested by the encountered faults.

It was concluded, in line with Lombardi's assessments, that the regular grouting measures, as the GIN is, pre-suppose a foregoing treatment of the cavities. On the other hand, the GIN method calls for the use of a unified stable mix with related unified viscosity and yield stress, which would be again of limited suitability, when sealing off a wide spectrum of joints, of different accessibility and degree of interconnection with large voids, is envisaged.

The discussed hypothetical possibility to "reset" the grouted volumes to zero upon filling of intersected cavities was assessed to be of limited practicability, since it would require the immediate identification of cavity grouting and the stage, when those are filled, during the running grouting procedure. As a conclusion, the application of the conventional, hold/refusal concept defined by grouting pressure was agreed. Still, even under given conditions, in rocks with large fractures, the GIN-method could be usable for the first grouting round for economically optimized sealing of the largest fractures, as long as a raise in grouting pressure can be observed.

The dominant rock layers are the result of dolomitization of a previously present limestone, whereby the dolomite is partially degraded and decomposed. That explains the presence of sandy pockets in dolomite rocks. These zones required special attention, as on the one hand they are hardly groutable with a conventional slurry, but on the other hand – exposed later to higher water pressures - they are eventually erodible. Treatment with higher grouting pressures than the later effective water pressure is expedient in these cases.

It could be observed, in the trial panel at riverbed, that the grout takes diminished significantly as the injection process progressed from primary, secondary, tertiary to quaternary holes. This observation actually reflects the increasing intensity of interlocking between the grout curtain around the bores with increased ranks (decreased spacing). Nevertheless, the closure effect was not fully evident considering some Lugeon tests results at greater depths in check-holes, possibly due to known disturbance zones, possibly with rather unsuitable orientation of discontinuity of surfaces, at the mentioned depth. In the upper parts of the curtain, the average Lugeon values of the Check-Holes were well below the specified values.

The conclusions and consequences drawn from the trial panels data considered, among others, the following aspects:

- Target-pressure based, refusal criterion was adopted. In case of major changes in rock properties, the refusal criterion consideration had to be re-evaluated accordingly.
- All bores were executed in descending method due to encountered higher fragmentation intensity of the rock mass and related instability of bore, despite numerous attempts to extend the drilling length beyond the length of 5-6-m-long single stages. Still, the attempts to apply the ascending method were continued in the new treatment sections targeting at time and cost optimization.
- The average takes decreased continuously from the Primary holes to Quaternary holes, indicating the existence of a general intercommunication of the crack network. Still to ascertain the grout accessibility into the tight cracks, particularly in the bores of tertiary and higher order, lower viscosity and hence higher mobility grouts proved to be more efficient.

7. Summary and Conclusions

The conditions at Jannah Dam required a flexible adaptation of the design and execution. The thickness of the clay layers, the diversity of the ground properties and the high static and hydraulic demands on the bulkhead imposed the use of a soil replacement method instead of a soil improvement method for its construction. The frequent and extensive fault zones in the rock called for a flexible adaptation of the originally specified GIN injection method.

References

[1] SATCOM: Geotechnical Investigations Jannah Dam Project (Feb 2015)

[2] Flora, A. et al: The diameter of single, double and triple fluid jet grouting columns: prediction method and field trial results. In: Géotechnique Volume 63 issue 11 (2013)