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Technical Note

Application of cement grouting for stabilization of coarse materials

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Abstract

In a rare engineering experience throughout the world, we successfully stabilized relatively coarse materials of drain using cement grouting. The grouting work was performed at the Karkheh earth dam, southwest Iran, and was part of the efforts to extend the dam's cut-off wall. Since the dam was completed, the execution of the new cut-off wall from the dam crest was inevitable. Hence, one of the main difficulties associated with the development of the new cut-off wall was trenching and execution of plastic-concrete wall through the relatively coarse materials of drain in the dam body. Due to high permeability of drain, the work was associated with the possible risk of excessive slurry loss which could result in the collapse of the trench. In order to achieve an appropriate grouting plan and to determine the mix ratio for the grouting material, a full-scale test platform consisting of actual drain materials was constructed and underwent various tests. Results of the testing program revealed that a grouting plan with at least 2 grouting rows and a Water/Cement mix ratio of 1/ (1.5-2) can successfully stabilize the drain materials. After finalizing the technical characteristics of the grouting work, the method was applied on the drain materials of the Karkheh dam body. The results were satisfactory and the drain materials were stabilized successfully so that the cut-off wall was executed without any technical problem.

Keywords: *Grouting, Cement grouting, Karkheh dam, Coarse material, Drain, Slurry loss, Cut-off wall.*

1- Introduction

Compared to other fields of civil engineering, grouting technique is relatively new and thus many new experiments and researches are necessary for its development. In the past century, this technique has been applied in many civil works including permeability reduction, improvement of mechanical properties and soil stabilization.

Especially, this method has been widely applied in the field of dam engineering with the emphasis on water sealing of dam foundations. Although considerable improvements have been introduced into the field of grouting of medium to fine materials in recent decades, there are many unknowns in the grouting of coarse materials. A tentative review of the international efforts in this field reveals that little research work has been conducted or at least published concerning the grouting of coarse materials. Almost all of the manuals (e.g., [1]), books (e.g., [2]), or scientific reports and papers (e.g., [3-6]) published in this field, concern either soils or rocks. This seems normal because almost in all of the ordinary engineering applications of grouting like water proofing of dam foundations, improving the mechanical properties of foundations, or stabilization of slopes, we are facing either soil or rock. It happens rarely to apply the grouting technique on other formations like coarse materials. However, during the construction of infrastructures like large dams, many complicated engineering problems may arise which make the applications of new techniques inevitable. We faced one of these engineering problems during the construction of the complementary cut-off wall of the Karkheh earth dam in southwest Iran which will be discussed in the following.

Here we report and analyze the application of cement grouting for stabilization of the coarse materials of drain at the Karkheh dam site (Fig. 1). The grouting work was employed in order to facilitate the execution of the dam's complementary cut-off wall. Part of this new cut-off wall should be performed

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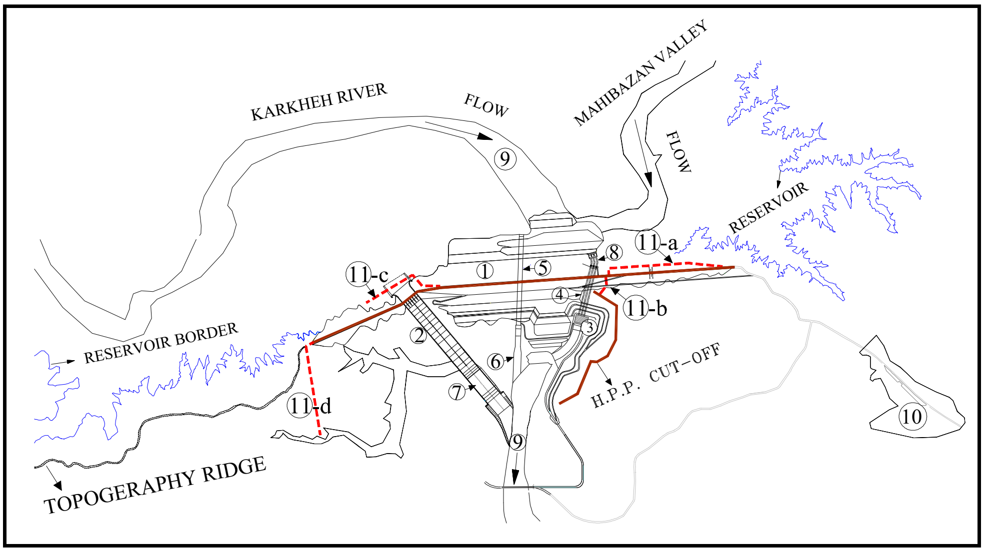


1. Dam crest
2. Spillway
3. Powerhouse
4. Power tunnel
5. Culvert
6. Stilling basin
7. Stilling basin
8. Intake shaft
9. Karkheh River
10. Offices
11. New Cut-off wall

Fig. 1 General plan of the Karkheh dam and hydropower project. The thick solid and dashed lines represent the old and new cut-off walls, respectively

through the dam body, and hence the stabilization of the drain material was a must (cut-off wall no. 11-b in Fig. 1). In Fig.1, the old cut-off wall is shown by brown solid line whereas the new (complimentary) one is shown by red dashed line. The old cut-off wall was performed before the construction of the dam body but the new one should be performed after the completion of the dam body from the dam crest.

To perform the plastic concrete cut-off wall, we need to drill and trench through the dam body and then, fill the excavated trench with cast-in-place plastic concrete. During each drilling and trenching activity, it is necessary to apply an appropriate drilling fluid in order to make sure that the trenching walls do not collapse. During the trenching of drain materials, since the medium is highly permeable, excessive slurry loss will occur, and thus it is necessary to reduce the permeability of the medium before trenching. We applied cement grouting to reduce the permeability of the drain. In the next sections, at first a short review of the Karkheh dam project will be presented, and then the trial grouting experiment will be discussed followed by the results of the actual grouting practice in the drain materials of the Karkheh dam body.

2. Karkheh project and the location of grouting

Karkheh storage dam is the largest dam in Iran in view of reservoir capacity with a capacity of around 7400 million cubic meters of water at the maximum water level. Karkheh dam and hydropower project is located on the Karkheh River, the third largest one in Iran in terms of flow discharge. Karkheh is an earth core rock-fill dam with a height and length of 127, and 3030 m, respectively [7]. The Karkheh dam provides about 4 billion cubic meter of regulated water to irrigate 320,000 hectares of downstream farmlands [8]. Figure 1 presents the general plan of the Karkheh project.

A plastic concrete cutoff wall was considered as the main water sealing system of the dam (solid brown line) [9]. In addition to the dam main cutoff wall, another cutoff wall can be seen in Fig. 1 which was performed at the north and east of the powerhouse to decrease seepage at the powerhouse slopes [10]. Figure 2 shows the extension of the dam main cut-off wall.

By impounding the Karkheh dam in 2001, excessive seepage was observed through the dam foundation [8]. This excessive seepage at the relatively high reservoir water level resulted in high uplift pressure at the dam toe and excessive hydraulic gradient of the discharging water through the dam foundation. By increasing the reservoir water elevation and reaching the elevation of 210.50 in March 2004, the necessity for taking remedial measures became evident. A series of remedial measures were implemented to improve the dam safety among which was the extension of the main cut-off wall both at the right and left banks of the Karkheh dam (cut-off walls 11-a, 11-b, 11-c, and 11-d in Fig. 1). The main objective of this measure was to keep the foundation uplift and hydraulic gradient of the discharged water within the acceptable limits [11].

The general plan of the mentioned complementary cut-off walls is shown in Figure 1. The execution of the complementary cut-off wall was a unique experience in this field and was associated with many technical difficulties which required most updated engineering techniques and equipments. Among difficulties encountered during the extension of the new cut-off wall were, connection between the new and old cut-off wall, trenching and execution of plastic concrete wall through relatively coarse materials including drain and filter, approaching the old cut-off wall, and finally construction of the connecting panel [12]. We discuss

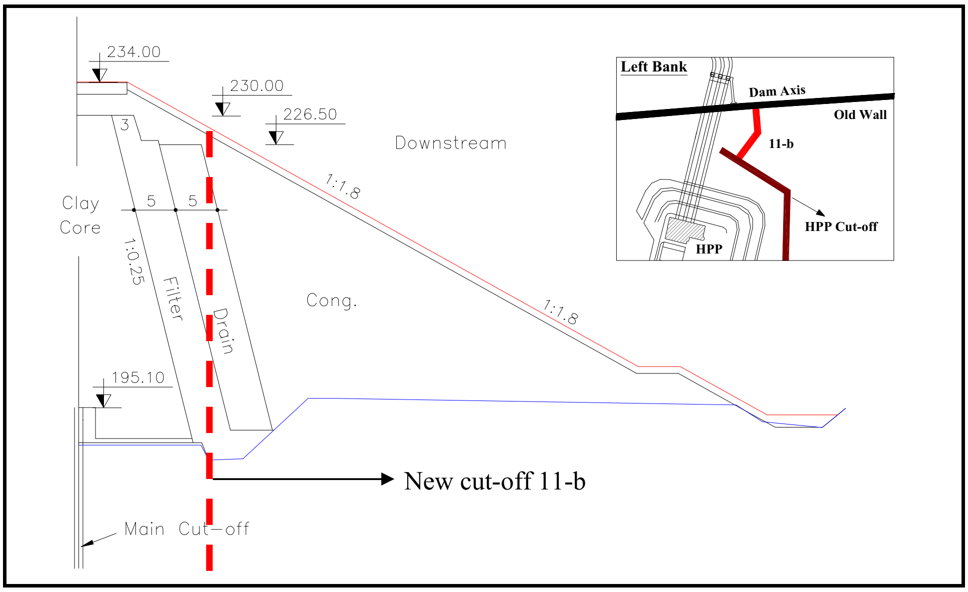


Fig. 2 A cross section of the Karkheh dam body at the location of the powerhouse connection cut-off wall (cut-off entitled 11-b in Fig.1)

one of these engineering difficulties in this paper which is trenching and executing the cut-off wall through drain. We faced this problem during the execution of the cut-off wall 11-b (Fig.1). To present a better image about the problem under study, we have shown a cross section of the Karkheh dam at the location of this cut-off wall in Fig. 2. As can be seen, the new cut-off should be executed from the dam crest and should pass through the drain in the dam body. Figure 3 shows the soil grading curve of the drain materials of the Karkheh dam body. According to Fig. 3, D_{10}, D_{30}, and D_{60} of the Drain material are 45, 55, and 75 mm, respectively. In addition, Fig. 3 shows that less than 5 percent of the material is passing through the sieve no. 200. Therefore, according to the Unified soil classification system [13], the drain material is classified as GP which means it is of the type of poorly-graded gravel. Density of the drain is 1825 kg/m^3.

3. Cut-off wall execution in drain

Execution of cut-off wall through coarse material of drain is associated with many difficulties. The main challenges in the trenching and execution of cut-off wall in drain arises from excessive slurry loss due to its high permeability. This could cause serious consequences including:

1) Excessive slurry loss on the one hand makes the execution of the wall impossible, and on the other hand, is followed by many risks. Slurry loss may cause the trench to collapse. In this case, the expensive trench-cutter will be buried at depths of the dam foundation creating a huge economical damage. The collapse of a deep trench may cause slope failure on the dam body too.

2) The excessive slurry loss through drain will pollute these materials and thus preventing it from its vital role of safe passage of seeped water.

Regarding above, special protective measures should be employed in order to prevent excessive slurry loss and also to stabilize the drain material. To reach this goal, the grouting technique was the only possible option. As discussed earlier, there were no experience in this field and thus, extensive trial grouting was done to reach appropriate grout mix design, pattern of grouting holes, required grouting pressure and other related technical information. In the next sections, the trial grouting experiments are discussed.

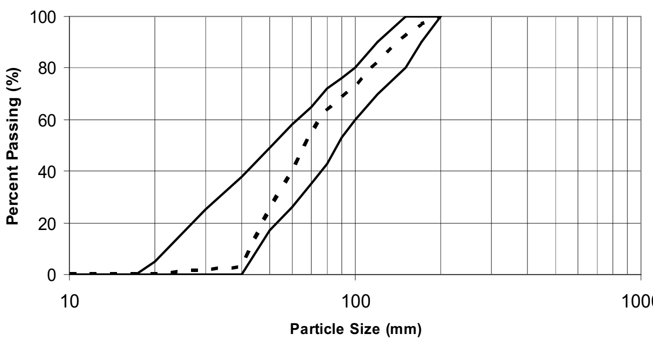


Fig. 3 The grain size curve of the drain material. The dashed line shows the average grading of the material

4. Trial grouting platform and results

Using the dam's actual materials, a trial platform with the dimensions of 20 m × 20 m was constructed in the site. Figure 4 shows the plan and a cross section of the platform along with the test holes arrangement on it. As shown, 8 grouting holes along with 8 test holes with a triangular pattern were used for trial grouting. It was a full-scale test and the materials used for the test platform were identical to the actual materials of the dam body. Two different series of grouting holes were used with different spacing (D series and DF series in Fig. 4) and were grouted using different mix designs. The grouting holes were named D1 through D5 for D series, and DF1 through DF3 for DF series (Fig. 4). The test holes were DC, DC1 through DC3, DFC, and DFC1 through DFC3 (Fig. 4).

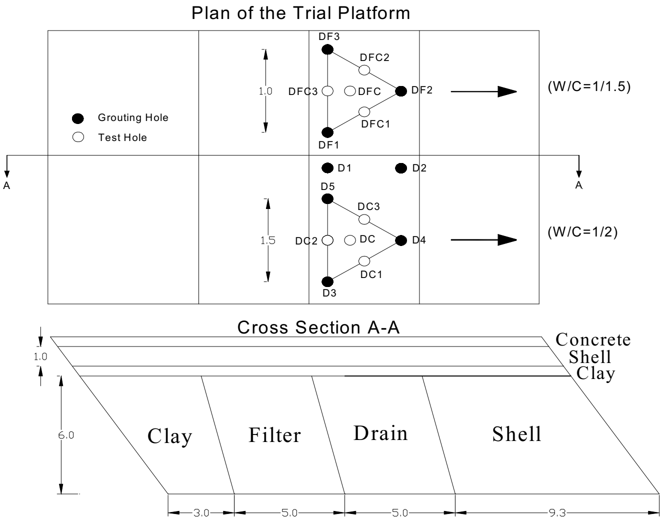


Fig. 4 Plan and a cross section of the trial platform for grouting of drain. Dimensions are in meters

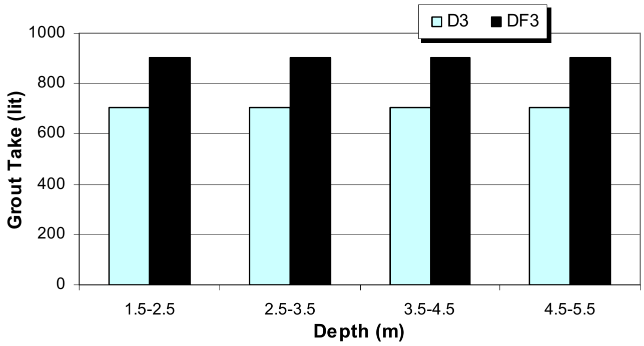


Fig. 5 Amount of grout take in D3 and DF3 grouting holes

All grouting and test holes were drilled to the depth of about 6 m. All of the holes were water-flushed rotary-drilled. Based on Fig. 4, the D holes were injected with cementitious grouts with a Water:Cement (W:C) proportion of 1:2 along with 10% by volume of bentonite, 1% of sodium silicate, and 0.5% of TEA (Tri Ethanol Amine). The mix design used for grouting in DF holes was the same as the D ones with the exception that the W:C proportion was 1:1.5. The down-hole method was applied for grouting in the holes. Since no tube-e-manchette was used in the grouting holes, the application of down-hole grouting technique was inevitable. To maximize the efficiency of the process, the grouting was performed in certain intervals such as 1 m, and re-drilling was used. To prevent possible excessive grout take, the grouting pressure was kept below 5 bar throughout the grouting process [1]. The US Army engineering manual for grouting technology was used as the guidance throughout the experiments. Figure 5 presents examples of the amount of grout take in some of the grouting holes. We note that we kept the volume of the required grout in each stage constant since the medium to be grouted was uniform.

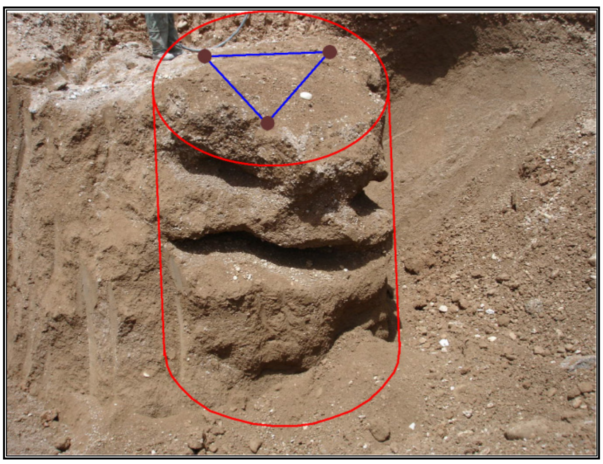
To assess the effectiveness of the grouting program, the water pressure tests were conducted at the intermediate holes (test holes). In the case of back water flow from these holes, it could be inferred that the grouting was successful. However, water take reveals that still there were unfilled voids in the medium. In total, the water pressure tests in the intermediate holes revealed that each grouting hole was capable of stabilizing up to the distance of about 0.5 m from its axis creating a stabilized cylinder with the diameter of 1 m around its axis.

The above pattern was confirmed through trenching of the trial platform after 48 hours (Fig. 6-a). The creation of a stable cylinder with the radius of about 0.5 m around the D holes is evident in Fig. 6-a. According to this actual observation, we were able to determine the pattern of the stabilization of the drain material through cement grouting. This pattern is shown in Fig. 6-b. We note that Fig.6-a shows that some parts of the drain remains untreated indicating that at least two rows of grouting lines are necessary for complete stabilization of the medium. In conclusion, the main findings of the trial grouting experiment can be summarized as follows:

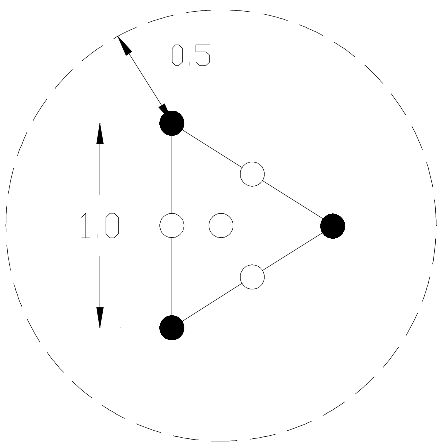
1. A cement grout with the W:C proportion of 1:1.5 to 1:2 along with a 1 to 1.5 m hole spacing is appropriate for grouting of drain materials

2. Application of at least two grouting rows is necessary to achieve a uniformly treated medium

3. The amount of grout take in drain is about 700-900 lit/m



(a)



(b)

Fig. 6 The stabilized drain around the D-series grouting holes (a) and the inferred stabilization pattern from it (b). Dimensions are in meters

5. Application of the method and actual results

After successful application of the cement grouting for the stabilization of the drain materials at the trial platform, we apply this method at the drain of the dam body. Before proceeding towards this, it is necessary to design the grouting plan. The main considerations for designing the grouting plan are:

- To limit the grouting range in the desired range
- To prevent excessive grout take
- To completely stabilize the medium without leaving untreated parts

Due to the above considerations, three circles as well as a row of grout holes were used as shown in Fig. 7 including P series at the outer side, T series at the middle, Q series at the inner side, and a row of holes in the center of the Q series. The role of the P holes is to produce a confined environment to introduce the subsequent grouting of the T and Q holes. It is evident that the excessive grout takes in the grouting of the P holes is likely, thus it is important to perform these grouting with relatively low grouting pressures and a relatively shorter hole-spacing.

A hole spacing of 1 m along with a relatively dense grout having W/C ratio of 1/1.5 was applied to the P holes. Throughout the process of grouting in the P holes, the exerting pressure was below 5 bars and the amount of gout take was carefully controlled. Figure 8 presents examples of grout take in two adjacent holes from the P series. Note that in Fig. 8, the hole P13 was grouted prior to P12.

As can be seen, the average grout take in each stage is about 1000 lit except for some special stages which can be attributed to the possible local complexities. However, wherever the grout take in one stage is little, the amount of the grout take in the neighboring stage is high. This emphasizes again that at least two rows of grouting is necessary.

Table 1 presents the details of the mix design used for grouting. As can be seen, the W/C ratio in the row grouting was reduced to 1/ (0.75). The reason was to prevent the high compressive strength of the grouted medium. Since the grouted area was going to be trenched by a special trench-cutter, it is important that the strength of the medium to be in the acceptable range. However, since the P, T, and Q series were grouted before the row grouting, we were certain that the excessive grout take would not occur.

Figures 9 and 10 present examples of grout take in the two adjacent holes from T and Q grouting holes, respectively. T6 and Q7 were grouted before T7 and Q6, respectively. These

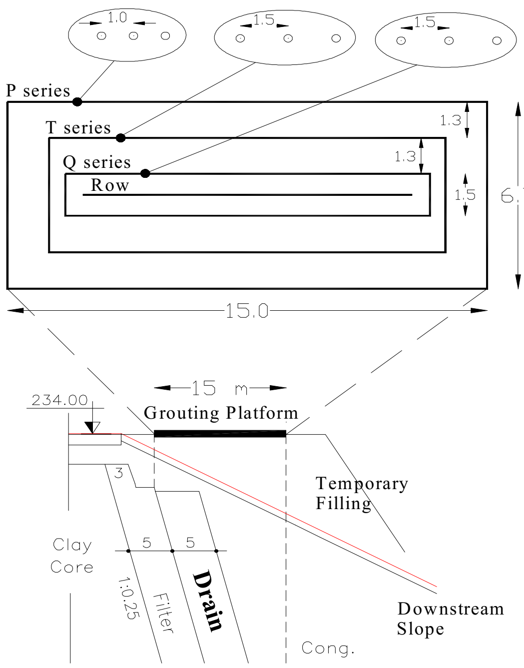


Fig. 7 Grouting holes and their location in the dam body. All dimensions are in meters

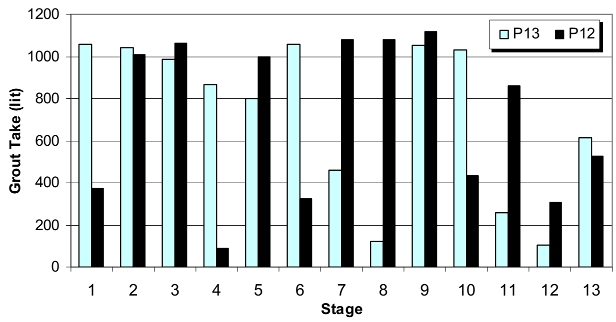


Fig. 8 Examples of grout take in two adjacent grouting holes from P-series grouting holes

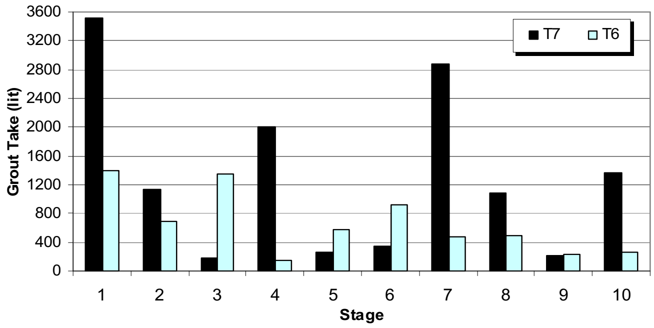


Fig. 9 Examples of grout take in two adjacent grouting holes from T-series grouting holes

Table 1 Details of the mix design used for grouting

Hole Name	W/C	B[1] (% of cement)	S[2] (% of cement)	CaCl[3] (% of cement)	TEA[4] (% of cement)
P	1/1.5	1	1	0.2	0.05
T & Q	1/1.5	0.5	1	0.2	0.05
Row	1/0.75	3	3	0.3	0.05

[1] Bentonite [2] Sodium Silicate [3] Calcium Chloride [4] Teri Ethanol Amin

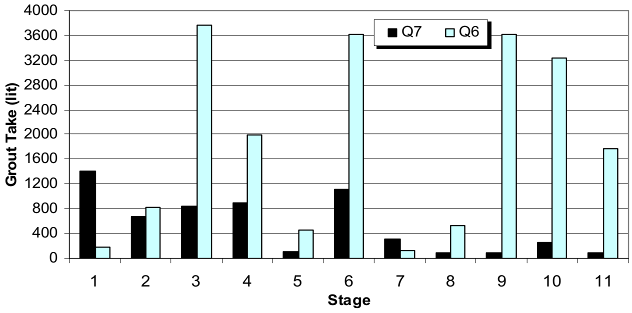


Fig. 10 Examples of grout take in two adjacent grouting holes from Q-series grouting holes

Figures reveal that except at some limited stages, the total grout take in the T and Q holes is reduced which can be attributed to the effect of grouting in the P holes.

After the grouting practice was completed, the supporting walls were executed through the drain since the medium was impermeable enough, and there was not the risk of slurry loss. Observations during the execution of the supporting walls showed that the grouting practice was successful in stabilization of drain. Table 2 presents records of slurry loss during the cut-off execution. It is clear that the rates of slurry loss are quite slow indicating the performance of the grouting of the drain material. However, Table 2 demonstrates that the rate of slurry loss in the Panel SPEH (1-6) is considerable. This panel is a contact panel at the interface of the drain and shell zones of the dam body. Generally, high rate of slurry loss in these interface zones is expected.

6. The method of drilling and grouting

Drilling in the drain was one of the challenges encountered during the project. The challenge was associated with the removal of the cutting materials from the hole in the shell material. It was observed that the water-flushing was not capable of removing the cuttings and thus, a relatively dense drilling fluid was employed. This fluid was a solution of bentonite and water with the proportion of Bentonite/Water: 1/10. All of the drilling works were of rotary type. In summary, the drilling and grouting of the grouting holes were composed of the following steps:

1. Drilling of the hole until the top of the drain material using a dense drilling fluid (as discussed above)
2. Installing a steel casing with the diameter of 131 mm until the top of the drain material and applying a weak grout around it
3. Leaving the hole for at least 24 hr for strength gaining

Table 2 Rates of slurry loss during the execution of the supporting cut-off wall

Panel Name	Level of Slurry Loss (m)	Rate (Cm/min)
SPEH(1-4)	11.5	5
	13	6
	17	6
	25	4
SPEH(1-5)	22	1
SPEH(1-6)	20	23

4. Drilling of the drain to the diameter of 96 mm with the interval of 1 m and using water-flushing
5. Grouting of the drilled section in the 30cm intervals

We note that, in our method, the grouting was performed through a dropper at the head of the driller. This allowed us to perform the grouting without removing the driller from the hole.

7. Conclusions

Grouting technique was employed to stabilize and to reduce the high permeability of the drain material of the Karkheh dam body. Based on the full-scale trial grouting and actual application of the method, the following conclusions can be made:

1. A cement grout with the water: cement proportion of 1:1.5 to 1:2 along with a 1 to 1.5 m hole spacing is appropriate for grouting of the Karkheh-type drain materials
2. Application of at least two grouting rows is necessary to achieve a uniformly treated medium
3. The grouting pressure should be limited to about 5 bar
4. To prevent excessive grout take, the application of at least two rows of circle grouting is necessary. In this pattern, the outer circle includes a relatively shorter hole-spacing along with a relatively dense grout.
5. The amount of grout take in the Karkheh-type drain materials is about 900 lit per stage of grouting

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