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RESEARCH ARTICLE

Evaluation of Grout Curtain Performance and Seepage Behavior in Doosti Dam, Iran

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ABSTRACT

Design and construction of civil structures such as dams require deep understanding of geological and geotechnical engineering conditions of rock masses in their site. Doosti Dam site consists of sedimentary rocks such as calcareous marl, siltstone, sandstone and sandy limestone of Mesozoic (Cretaceous) and early Tertiary of the Kopet-Dagh basin. In this study, permeability and hydraulic conductivity conditions of dam site were evaluated based on Lugeon tests and were presented as maps. Additionally, rock mass discontinuities in dam site and their properties were determined. The effects of geological engineering properties of discontinuities and permeability of different rock units on grout takes in the grout curtain were assessed. To compare the results, grouting performance was presented in the form of iso-cement take curves in the curtain rows. Finally, areas with poor performance were determined based on the obtained information. These points are pathways for water escape and pose risk on dam's stability during operation, which mandates a re-grouting program.

Key words: Engineering Geology, Seepage, Grout Curtain, Lugeon, Cement Takes.

INTRODUCTION

The greatest causes of failure in earth and rock-fill dams are dam overtopping, erosion due to seepage through dam body and foundation(piping) and the weakness in foundation (ICOLD ,1995). Due to the presence of discontinuities with unknown properties, there is a need to reinforce and improve the engineering properties and water tightness of rock mass. Grouting is a method often applied as a soil and ground improvement method. Grouting can be defined as the injection of flowable materials into the ground (usually) under pressure to alter and/or improve the engineering characteristics and/or behavior of the ground. Modification of the ground by filling voids and cracks dates back more than two centuries (ASCE 2010, Weaver and Bruce 2007).Construction of grout curtain by cement injection is the most common method of bedrock improvement (Houlsby 1992, Verfel 1989, Deer 1982). There are several examples of application of grout injection to rehabilitate the dam site. (Ewert 1985, Waver1991, Lombardi 2003,Warner 2004). The effectiveness and quality of grouting is controlled by numerous factors(Bruce&Dreese, 2010).Geological factors including geological formations in the region, the bed rock location, engineering properties of soil and rock, discontinuities, permeability, etc. have significant role in the successful construction of grout curtain. Among these, the number and the arrangement of discontinuities as water transfer and flow pathways are of special importance (Ewert, 2005).

Doosti Dam is constructed on Hariroud River in northeastern Iran on the border of Iran and Turkmenistan As shown in Figure 1. The dam is located about 180 km east of Mashhad, 75 km south of Sarakhs and 4 km upstream of the old bridge (Khatun bridge) in 61° 09.50' east and 35° 56.30'north. It is a rock-fill dam with silty core. Its height is 78 m above foundation, the crest is 670 meters long and 15 meters wide. The heel is 416 meters wide and its capacity in the normal level is 1250 million cubic meters.

Geology of the dam site

The project is extended through the easternmost parts of Hezarmasjed-KopetDagh tectonic zone. The Kopeh Dagh is a linear mountain range separating the shortening in Iran from the stable,flat Turkmenistan platform (Berberian&Yeats 1999,Walker&Jackson 2004). The Dam site is located in the northern ridge of an anticline with a general trend of NW-SE. In this area Hariroud is flowing through the rock strata from east to west. In the dam location, the overall slope of the valley walls is 30-35 degrees and the valley is U-shaped and symmetrical. Doosti Dam is constructed on hard calcareous and sandstone rocks on the right side and loose rocks including calcareous, marly and argillitic shale on the left side. Geological longitudinal profiles along the dam axis is presented in figure 2 .The oldest rock unit, which is in Abtalkh formation, is in the southernmost part of the dam axis where the spillway is located. It consists of blue to gray marls with interlayers of gray siltstone and thin argillite layers in the lower parts, fine grained calcareous siltstones and sandstones with fossiliferous blue to gray marl cement in the upper parts, and the total thickness of approximately 650 m. This is continued by Naeyzar formation consisting of fine to medium grained green glauconitic sandstones with interlayers of intensely eroded siltstones having numerous joints and fractures with 135 meters of thickness. The right abutment consists of rocky Kalat formation including alternations of sandy limestone, brown sandstone and siltstone and gray calcareous shale 220 m thick with abundant joints and fractures and minor faults. Continental red sediments of Pesteligh formation with high thickness are located on the Kalat formation and in contact with the dam lake on the right side. This formation consists of alternations of red sandstone, shale and siltstones with marl or argillite thin layers and a thick red conglomerate layer in the upper part. All rock layers of these formations have average strike of N85W and slope of 60-65 degrees towards the northeast.

Discontinuities system assessment

According to Palmström & Stille (2010) engineering properties of rock mass depend far more on the system of geological discontinuities within the rock mass than on the strength of intact rock.Acquiring reliable data on rock discontinuities is necessary in almost every engineering project. In a dam site, discontinuities highly affect the foundation's strength and deformability, groundwater flow, water escape from the reservoir, slopes and tunnels stability, ease of blasting and the resulting blocks, and groutability of the foundation rock.

Various research to assess the general trend of geological structures in eastern Kopet-Dagh show that the overall resultant compressional forces in this region is in the northeast direction(Zamani,B., Angelier , Zamani,A., 2008). The forces on the dam site have formed geological structures, faults, and joints and fractures systems.

Existing faults in the area with overall trend of NE-SW and NW-SE have affected the rock mass in the dam site and sometimes resulted in displacement. Since the existing faults are small and have no significant effect on the overall structure of the dam site, their behaviors are not assessed here.

Joints, fractures and beddings

Doosti Dam discontinuities were studied in a thorough joint study campaign on the rock foundation in left abutment, bedrock and right abutment in the process of grout gallery construction. The gathered data were statistically analyzed using DIPS software. The results indicate that there are three main joint sets in addition to the bedding(Table 1).

The assessment of geometrical properties of discontinuities indicate that the bedding strike (E-W) is approximately perpendicular to the dam axis (N-S) and the bedding dip is directed toward the right side (NE). Bedding has the highest potential in water transmission from the dam lake to the downstream. Joint sets J1 and J2 have seepage potential as well. A comparison among the properties of discontinuities surfaces shows that these properties are similar to each other. Most of joints surfaces are smooth, mostly without filling and oxidized. Silt and clay are the major filling materials followed by calcite and gypsum. Their continuity is medium to high (3-10m) and their openness is less than 2.5 mm. Structural condition of joints and bedding surfaces in the dam site is presented in figure.3.

Evaluation of dam site seepage

Study of water movements and transmission in the site's rocks is essential in hydraulic structures. Safe and economic design of such structures requires sufficient information about the permeability of the foundation rock mass. Lugeon test is the most common test to determine the permeability of the rock strata. The test results are strongly related to the geometrical properties and weathering degree of water pathways (discontinuities) (Ewert 1997, Wei Jiang X. et al. 2009).

The rock permeability in abutments, foundation and dam structure in the depths were assessed using Lugeon test results in boreholes excavated for the phase I and II of study and A series boreholes during the implementation of grout curtain along the dam axis. The results are presented as Lugeon value iso-lines in figure 4.

As depicted in figure 4, the left abutment is impermeable and in maximum have very low permeability from near surface to the depth of 5 meters (LU<3). The rock foundation from the spillway area to the depth of 10 meters have low permeability (LU=3 to 10) and is impermeable in higher depths.

The foundation rock in the middle part of the dam or the river bed in the Iran section, have high to medium permeability (LU=10 to 60) to the depth of 25 meters below the grouting gallery. By increasing depth, permeability is decreased and below 35 meters of depth, the foundation rock becomes impermeable. In the Turkmenistan section, to the depth of almost 40 meters, it has medium (LU=10 to 30) to very high (LU>60) permeability and below that depth, it starts decreasing such that below 50 meters, permeability is decreased to values lower than 3 Lugeon.

Rock quality designation (RQD)

Analysis on cores recovered from first and second phase of excavations in Doosti Dam shows that the specific rock mass quality in lithological units of dam foundation area decreases near surface and apart from the fault paths, increases in the depths. Table 2 shows RQD values for different parts of the Doosti Dam site.

Grout curtain of doosti dam

Construction of grout curtain by injection is one of the common methods of maintaining the hydraulic stability of earth dams to prevent leakage and internal erosion of dam foundations. Grout curtain of Doosti Dam is 1125 m long, from which 335 meters is in right abutment and open space, approximately 225 m in the foundation or bedrock and 535 m in the left abutment to the end of spillway entrance platform. Specifications and longitudinal section of Doosti Dam grout curtain are presented in Table 3 and figure 5 respectively.

Assessment of grout curtain

Right abutment and open space

There are various quality assessment methods for grout curtain injection. One of these methods is the amount of cement loss in grout curtain borehole rows. Based on this, it is essential to have a criteria for cement loss assessment. In this research, Deere (1982) descriptive classification with minor modifications was used for cement loss classification and comparison in different injection sections is showen in Table 4.

Iso-cement take curves

Based on the cement loss data, iso-cement take curves were drawn by Surfer as shown in figure 6. Based on this figure, exact location of points with high cement take was determined and cement take variations in different rows were compared. Finally, successful injection operation decreased the foundation rock permeability and increased the efficiency of grout curtain in the designated areas.

As shown in figure 6, assessment of iso-cement take curves in the first row of grout curtain in the right side indicate that there are numerous areas with medium to high cement take. These areas are located in the right abutment in grouting gallery to the depth of 15 meters and in the open space to the depth of 40 m. A linear zone with 100 meters of depth is observed at the end of grouting gallery in the right abutment with very high cement take which have high cement take in the next two rows as well.

Cement take in the second row boreholes in the right abutment and open space are decreased significantly (less than 50 kg/m). However, there are still points with medium to high cement take that are mostly located in the open space.

In the additional row boreholes, cement take in most of the points in the right abutment and open space are decreased to very low values (less than 12.5 kg/m). Linear zone at the end of grouting gallery and another zone in open space still have medium to high cement take. These zones are weak points and have the potential to transfer reservoir water to the downstream. Finally, the amount of rock cement take in the right side is decreased by implementing continuous rows of grout curtains.

Foundation or river vally

In the middle part of the Doosti Dam, three rows of boreholes were excavated and grouted from inside of the grouting gallery. shows iso-cement take curves of the grouting curtain boreholes in the middle part of the dam and the following results were obtained(Figure 7) .

In the first row boreholes of the grouting curtain (vertical boreholes), most of the cement take were in surficial parts below the grouting gallery to 10 m depth. Cement take is Iran section of the dam is more than the Turkmenistan section.

Cement take was substantially decreased in the second row boreholes. In both sides of water diversion gallery, besides from a few sections, the cement take was below 50 kg/m. This decrease in cement loss shows the success of the first row of grouting.

In the additional row, cement take in the rock units on the right side of water diversion gallery reached to less than 50 kg/m. However, in the left side, with the increase in the boreholes angles, there were points with medium to high cement take. Appearance of these points was due to the high angle of boreholes compared to the Turkmenistan section.

Left abutment and spillway

Left abutment and spillway of Doosti Dam are located on the fine grained calcareous sanstones, siltstones with interlayers of marl and argillite and calcareous marls of Abtalkh formation with very low permeability. Therefore, grout curtain in this part is implemented in one row and to the maximum depth of 20 meters. Figure 8 shows iso-cement take curves in this part.

As depicted in this figure, cement take in the left abutment in most of the points is below 50 kg/m. In the spillway part, there is more cement take which is mainly due to the surficial weathered joints, but in the depth the rock is impermeable.

Control boreholes

After implementation of the grout curtain, control boreholes were excavated to assess its performance. These boreholes were dug with angles 10 to 40 degrees from vertical towards south and then 15-minute Lugeon tests were conducted inside them. Then they were grouted and the results were presented as the iso-cement take curves as depicted in figure 9.

As depicted in figure 9, in most parts of the grout curtain, the cement take is reduced to less than 50 kg/m. The only place with high permeability and high cement take was some part of the foundation in the Iran section and the open space in the right side where there was contact with the lake. This has caused water escape and other problems in the operation of the dam.

RESULTS AND CONCLUSION

Doosti Dam site is composed of various formations with different hydrogeological characteristics. Based on Lugeon tests left abutment, spillway and a part of the dam foundation in Iran section have no water escape potential due to the Abtalkh formation containing marls and siltstone. Neyzar, Kalat and Pesteligh formations under the right side of the dam have great potential for reservoir's water transfer through bedding surfaces and joints.

The left abutment of the dam is impermeable and in maximum have very low permeability from near surface to the depth of 5 meters (LU<3). The foundation rock under the spillway to the depth of 10 meters have low permeability (LU=3 to 10) and after that becomes impermeable. The foundation rock in the middle part of the dam to the depth of approximately 40 meters have medium (LU= 10 to 30) to very high (LU>60) permeability. By going deeper permeability decreases, and deeper than 50 meters it reaches values less than 3 LU. Rock units in the right abutment to the depth of 25 meters below the grouting gallery have medium to very high permeability. Below this depth the permeability decreases with few exceptions where the rocks still have high permeability (LU>60). In rock units outside the dam body in Turkmenistan section, permeability is low (LU=3 to 10) to a maximum depth of 15 meters and after that the rock becomes impermeable (LU<3).

Grout curtain in the right abutment and foundation of the dam include 2 main and one additional rows which were implemented from grouting tunnel and gallery. The curtain is extended to the open space in the right side in a single row and in 3 stages with different distances. Grout curtain in the left side of the dam and in the left abutment is built in one row from grouting gallery and continued to the spillway part in the open space. Generally, the cement loss in the right side and foundation of the dam is much higher than the left side.

In the right abutment and open space grout curtain, there is no coordination between Lugeon results and cement loss. Points with medium to high cement take in the foundation and open space control logs show that there are still zones with permeabilites higher than 3 LU after the implementation of the grout curtain. These points are pathways for water escape and pose risk on dam's stability during operation which mandates a re-grouting program.

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Table 1. Geometrical properties of discontinuities in Doosti Dam site

Right abutment				Left abutment and River Bed				Location
J3	J2	J1	Bedding	J3	J2	J1	Bedding	Discontinuity
114	214	278	014	117	197	278	011	Dip Direction (deg.)
66	64	70	64	51	68	43	63	Dip (deg.)

Table 2. Rock Quality Designation for Doosti Dam site (Tooss Ab Consulting Engineers, 1999).

<table>
<tr><th>Lithology</th><th>Number of Fractures in Length Unit F/m</th><th>Rock Quality</th><th>RQD %</th><th colspan="2">Location</th></tr>
<tr><td>Sandstone, Sandy Limestone, Siltstone with thin Argillitic layers</td><td>6</td><td>Fair</td><td>60</td><td colspan="2">Right Abutment</td></tr>
<tr><td>Siltstones with interlayers of Marl and Sandstone</td><td>3</td><td>Fair</td><td>71</td><td colspan="2">River Bed</td></tr>
<tr><td rowspan="2">Argillitic and Marl Rocks</td><td>6</td><td>Fair</td><td>66</td><td>Upper</td><td rowspan="2">Left Abutment</td></tr>
<tr><td>3</td><td>Good</td><td>85</td><td>Lower</td></tr>
<tr><td>Marl</td><td>2</td><td>Fair</td><td>72</td><td colspan="2">Spillway</td></tr>
</table>

Table 3. Specification of grout curtain boreholes in Doosti Dam

Left abutment and spillway	**Foundation or middle part**			**Right abutment and grouting gallery**				**Open space in right side**	**Location**
First Row	Additional row	Second row	First row	Additional row	Second row	First row		First row	
Zero 30E Series	40, 30	30, 20	zero	30, 18	18	5	Right abutment	5-37	Inclination of boreholes (deg.)
				30	zero	zero	Grout gallery		
3895	2437	5007	3793	1865	4182	3949		12531	Total Drilling Length (m)
20	50			80				100	Max Borehole Depth (m)

Table 4. Proposed grout consumption classification

Very high				**High**	**Relatively high**	**Medium**	**Relatively low**	**Low**	**Very low**	**Description**
10000-500000	4000-10000	1000-4000	400-1000	200-400	100-200	50-100	25-50	12.5-25	<12.5	Cement Take (kg/m)

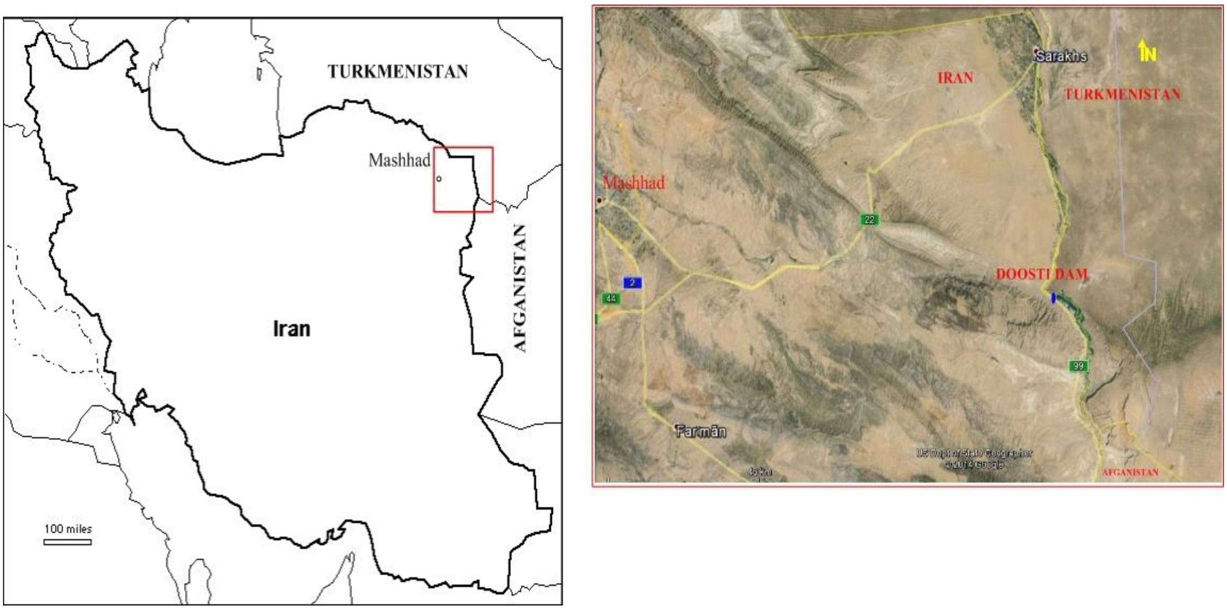

Figure 1. Geographical location of doosti dam and access routes

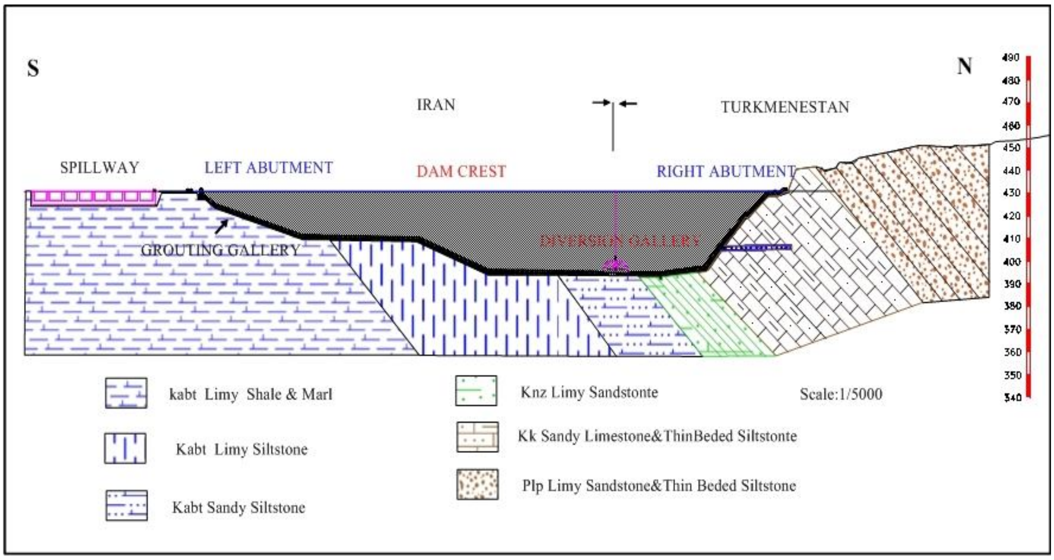

Figure 2. Geological profile along the dam axis

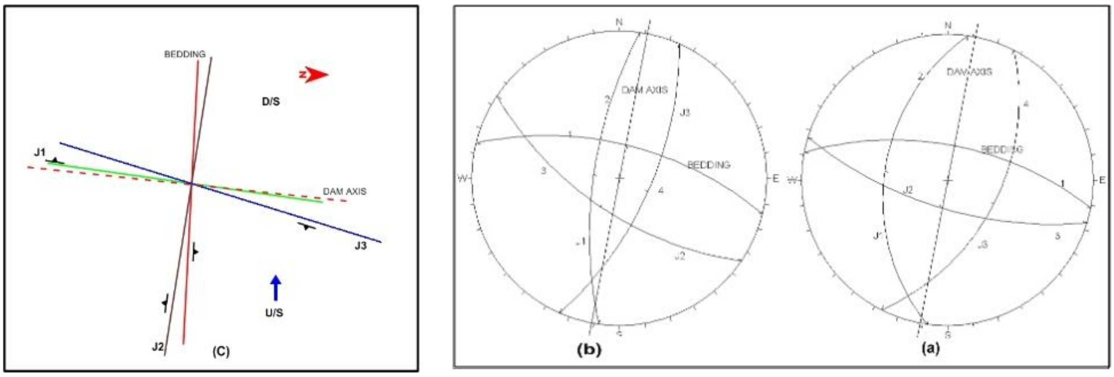

Figure 3. Geometrical properties of discontinuities in dam site (a) right side(b) foundation & left side and (c) discontinuities position with dam axis

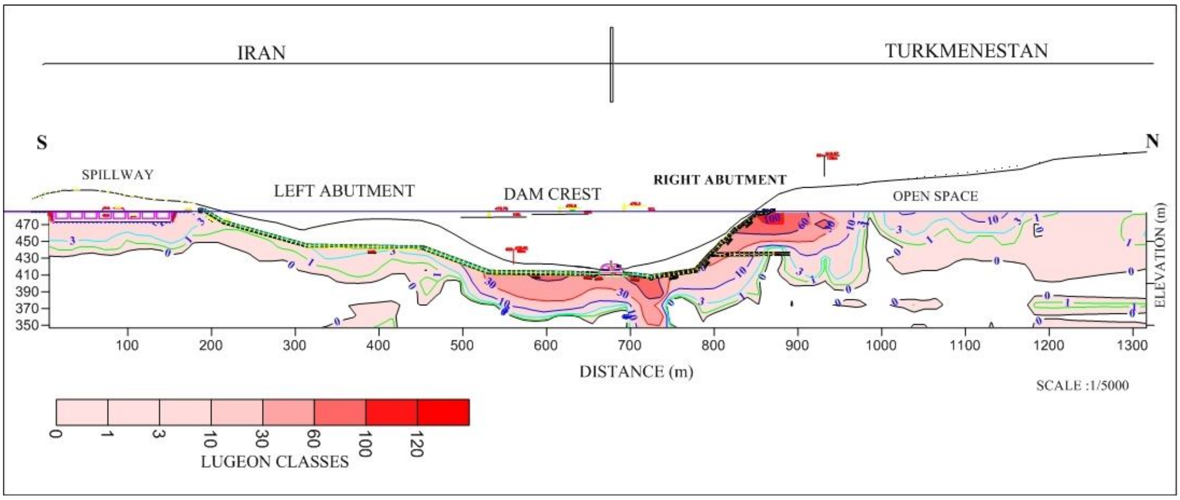

Figure 4. Lugeon value iso-lines along axis of doosti dam

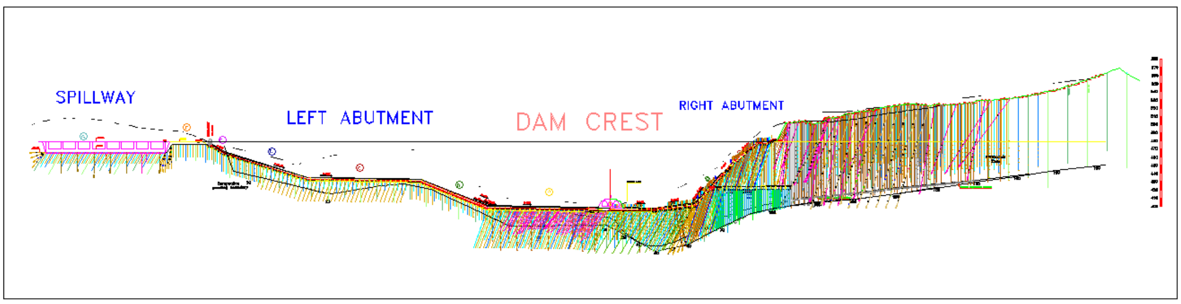

Figure 5. Grout curtain borehole arrangement in doosti dam (culham co. 1999)

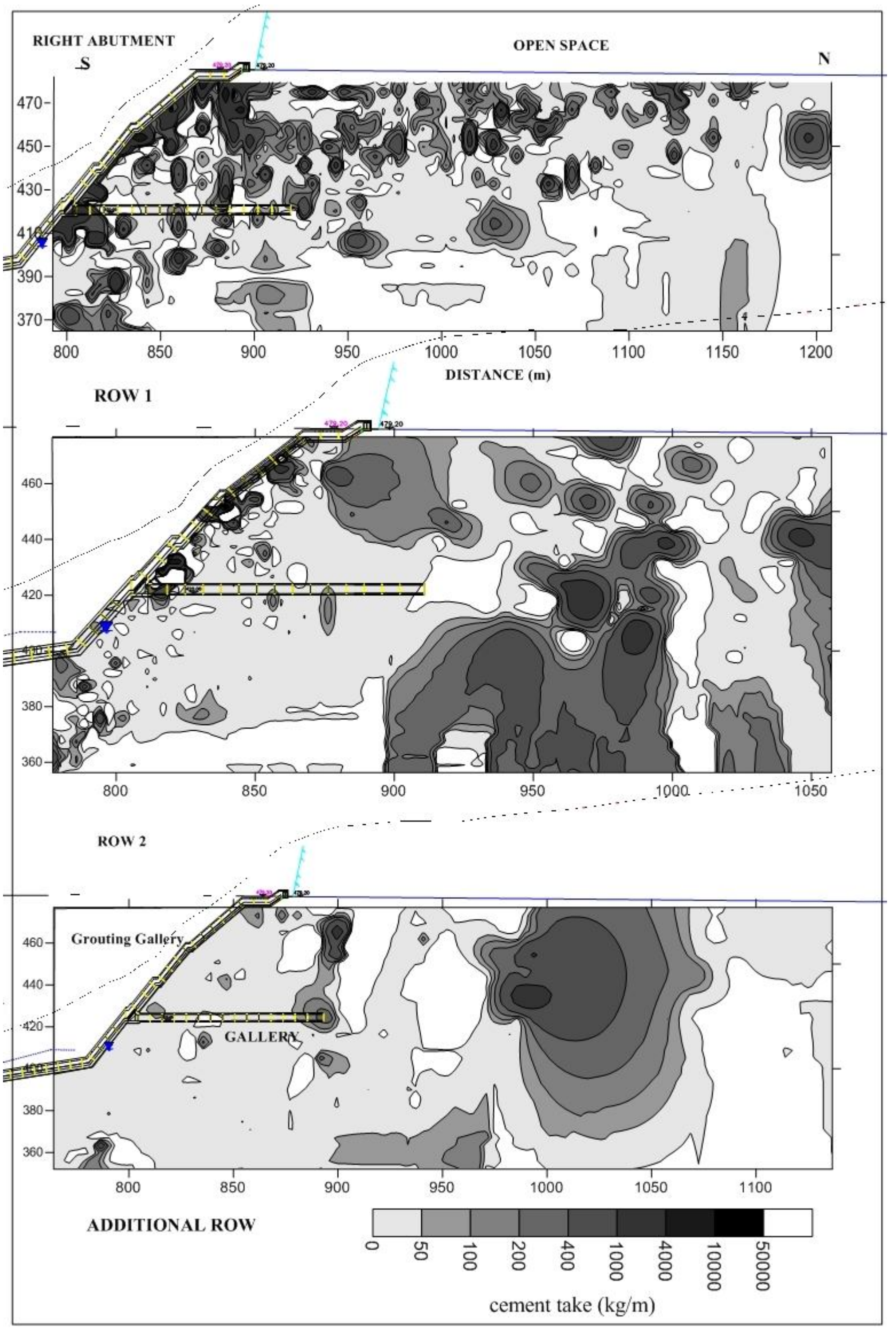

Figure 6. Iso-cement take curves of the right abutment of doosti dam in the first, second and additional rows.

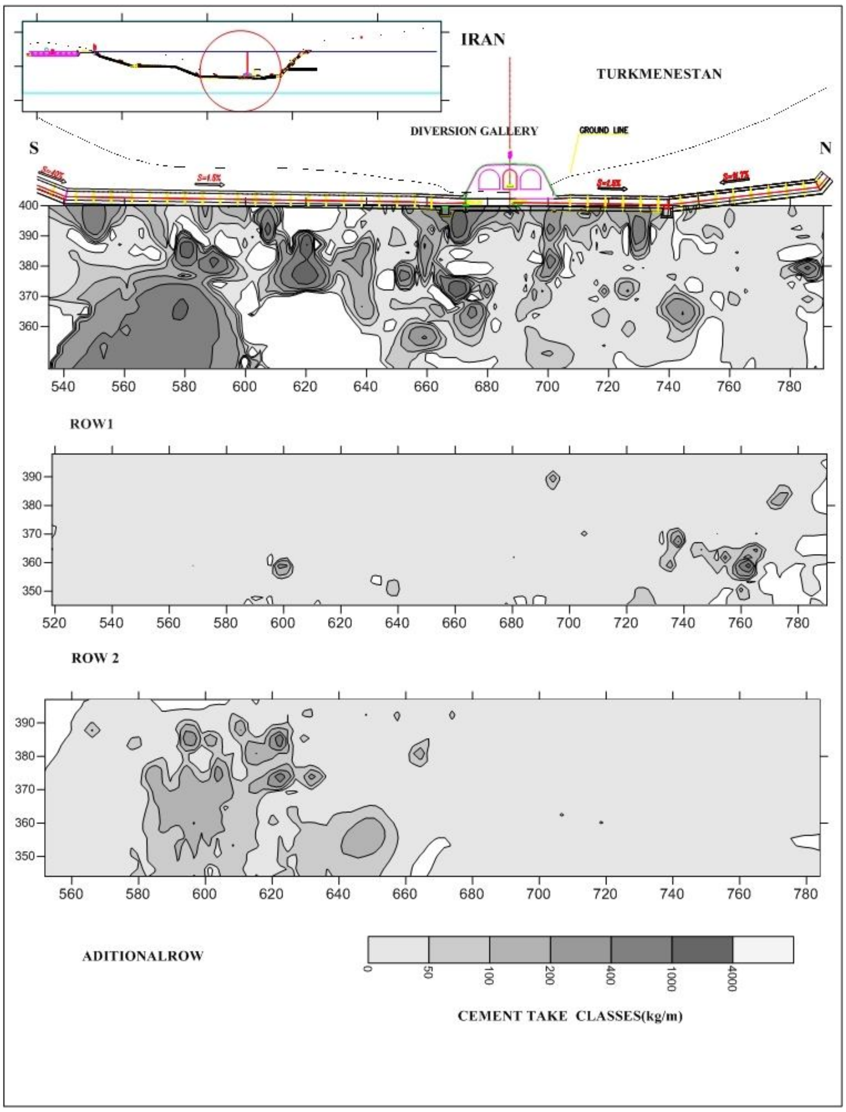

Figure 7. Iso-cement take curves of the grouting curtain in the middle part of the dam

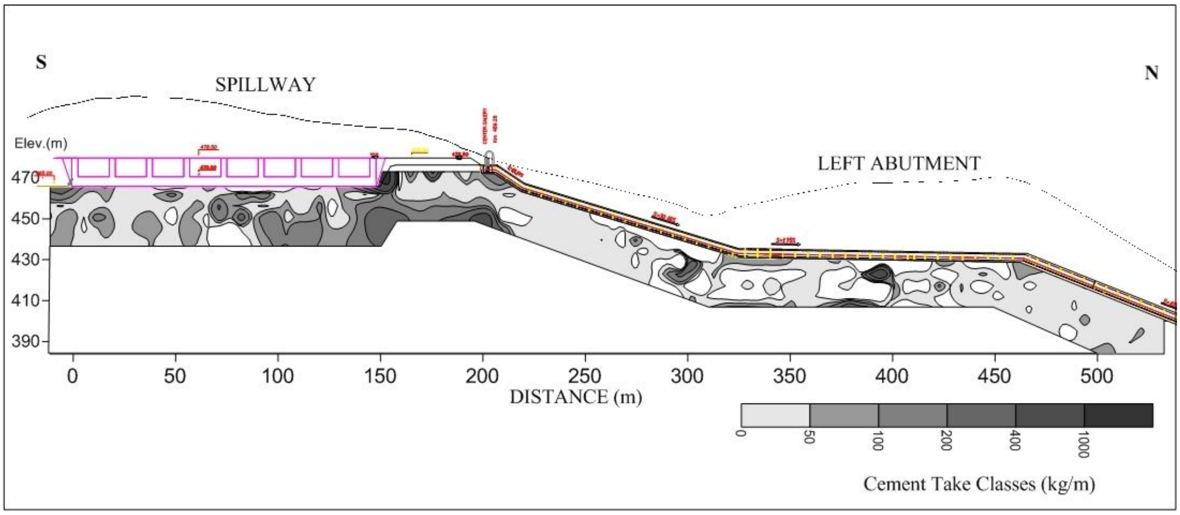

Figure 8. Grout curtain iso-cement take curves in the left abutment and spillway

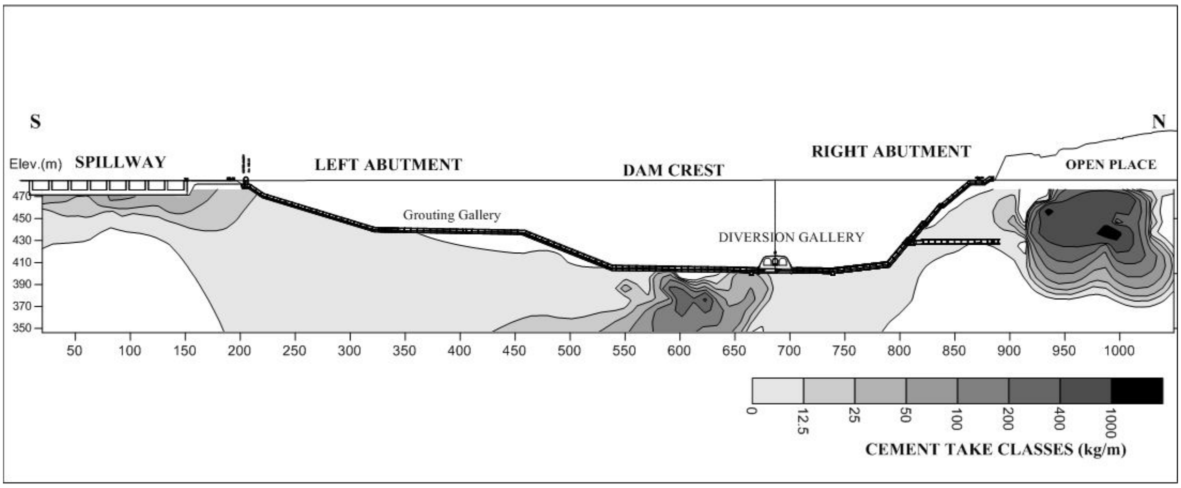

Figure 9. Iso-cement take curves in control boreholes