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Curtain Grouting Applications in Wala Dam (Jordan)

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INFORMATION

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ABSTRACT

Due to the influence of geological structures such as bedrock masses, stratigraphic planes, fracture systems, shear zones and faults, potentially concentrated water seepage is observed along dam foundations during operation and water retention. To achieve water tightness in bedrock masses, curtain grouting is a common method. In this study, the curtain grouting of the Wala Dam in Malih village of Madaba city, 30 km southwest of Amman, Jordan, was investigated. Due to the influence of geological structures such as bedrock masses, stratigraphic planes, fracture systems, shear zones and faults, potentially concentrated water seepage is observed along dam foundations during operation and water retention. To ensure water tightness in bedrock masses, curtain grouting is the most common method. In the field studies, core drilling, pressurized water tests, laboratory tests were carried out and grouting curtain length and mixture ratios to be used in grouting were determined. Within the scope of the project, a total of approximately 55.000 meters of drilling was carried out and an impermeable curtain was formed by grouting in these wells. The depth of the injection curtain was calculated to be socketed into the massive Upper Tafila Formation, which is considered impermeable according to Lugeon values. As a result of the curtain injection works carried out at Wala Dam, impermeability was ensured.

1. Introduction

In dam construction, the bedrock masses on which the dam body will rest, geologic structures such as stratigraphic planes, fracture systems, shear zones and faults are most likely to represent seepage channels potentially concentrated along abutments and dam foundations during operation and water retention (Dou et al., 2020; Yang et al., 2021; Risharnanda et al., 2023).

Therefore, in dam constructions, some precautions must be taken to ensure the impermeability and stability of the bedrock on which the dam will sit. The most common of these measures is excavation along the dam axis up to the bedrock and grouting of the bedrock. Grouting can be applied to structural and lithological defects within the soil or between the soil and is defined as the pressurized filling of fluid material, usually from boreholes, into the spaces between the structure (Kutzner, 1991; Kutzner, 1996; Alkaya and Yeşil, 2011).

Curtain grouting, is a proven method for sealing and waterproofing a variety of structures, including foundations, walls and underground structures like tunnels and basements. Grouting is commonly performed to seal the permeable rock fracture-thus limiting the groundwater seepage through the rock mass in underground constructions such as tunnels and dam foundations. By injecting grout into the rock mass, the hydraulic conductivity of the rock mass is expected to be reduced after the grout hardens (Houlsby, 1990; Weaver and Bruce, 2007; Gustafson, 2012; Stille, 2015).

In recent decades, extensive research has been aimed at theoretically describing various aspects of rock grouting, including hydrogeology in the rock mass (Zimmerman and Bodvarsson, 1996; Gustafson, 2012; Hernqvist et al., 2014; Zou et al., 2015; Hakansson, 1993; Eriksson and Stille, 2003; Eklund and Stille, 2008; Draganovic´and Stille 2011; Draganovic´and Stille, 2014; Gustafson and Stille, 2005;

Stille et al., 2009; El Tani, 2012; El Tani and Stille, 2017; Funehag and Thorn, 2018; Zou et al., 2018, Zou et al., 2020; Lombardi and Deere, 1993; Brantberger et al., 2000; Gothall and Stille, 2009; Rafi and Stille, 2015; Axelsson, 2009; Stille et al., 2012; Zhang et al., 2022).

In this study, the curtain grouting applications at Wala Dam (Jordan) were investigated. Wala Dam (Jordan) Project was constructed for irrigation and groundwater level regulation. The middle part of the dam is made of roller compacted concrete and the right and left bank parts are made of clay core rock fill. The 50-meter-high dam, which started to hold water in 2002, experienced water overflows during the rainy season due to insufficient reservoir volume. To ensure dam safety and increase the water holding capacity, a project was initiated in 2017 to raise the dam body by 15 meters. Since the increase in the body length will lead to an increase in the volume of water to be retained and the expansion of the reservoir area, the injection tunnels previously drilled on the right and left banks were extended and a new curtain injection project was prepared. Thus, the length of the impermeable curtain was deepened and extended.

2. Wala Dam

The Wala Dam is located in the village of Malih in the city of Madaba, 30 km southwest by road from Amman, the capital of Jordan. To the west of the dam, 55 km by road, is the Dead Sea (Dead Sea). Transportation is provided by asphalt road until the dam construction site entrance. Some properties of Wala Dam are given in Table 1.

Table 1. Properties of Wala Dam

No	Property	Value
1	Type	Roller compacted concrete + clay core rock embankment
2	Aim	Irrigation and groundwater level regulation
3	Height (m)	65
4	Length (m)	480
5	Total of backfill volume (m^3)	121.000
6	Concrete volume (m^3)	138.000
7	Storage volume (m^3)	9.300.000

During the project design phase, the geology of the region was analyzed through literature studies. These studies were supported by drilling and pressurized water tests and geotechnical properties were revealed. The drillings revealed Lower Mujip Limestones, Upper Mujip Limestones, Lower Tafila Member Chert, Upper Tafila Member Limestones and Sandstones, Dhiban Member Limestones in order from old to young. Until the Lower Mujip Limestone formation is reached, units with decreasing water permeability from the surface to the depth are crossed (Fig. 1).

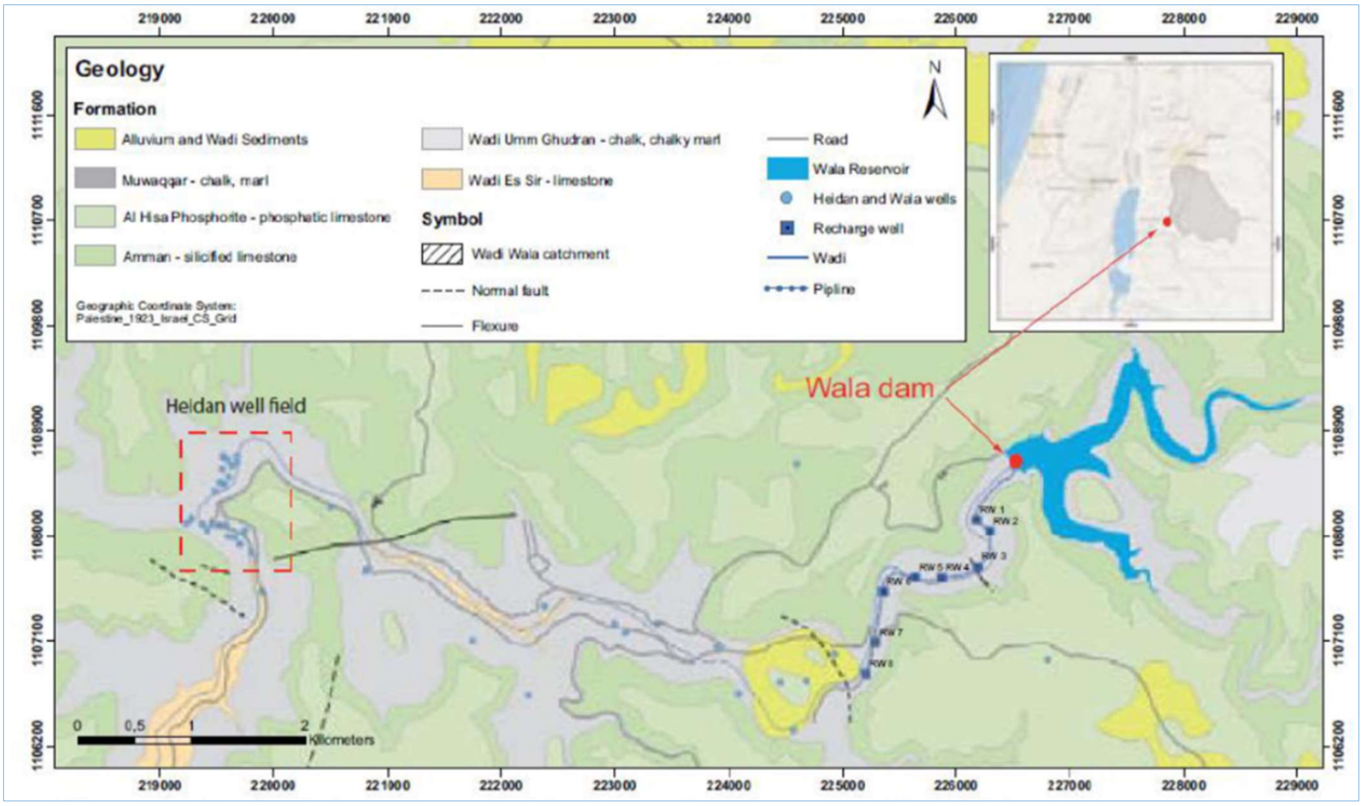

Fig. 1. Geological map of the Wala Dam Area (Hesham Al-Hesa, Jordan Valley Authority)

Table 2. Mixture ratios used in the injection applications

Mixture	Cement/ water ratio	Cement		Water		Sand		Bentonite			Bentonite/water mixture		Final mix		Density
	(%)	kg	lt	kg	lt	kg	%	%	kg	lt	kg	lt	kg	lt	gr/cm^2
M3	0.8	100	31.7	105	105	0	0	2	2	0.7	22	20.7	228	158.3	1.44
M4	1	100	31.7	90	90	0	0	1	1	0.4	11	10.4	202	133	1.52
M5A	1.42	100	31.7	60	60	0	0	1	1	0.4	11	10.4	172.5	103.4	1.67
M5 550	1.42	100	31.7	65	65	50	50	0.5	0.5	0.2	5.5	5.2	222.5	122.5	1.82
M6	2	150	47.6	67.5	67.5	0	0	0.5	0.8	0.2	8.3	7.8	228	124.8	1.83

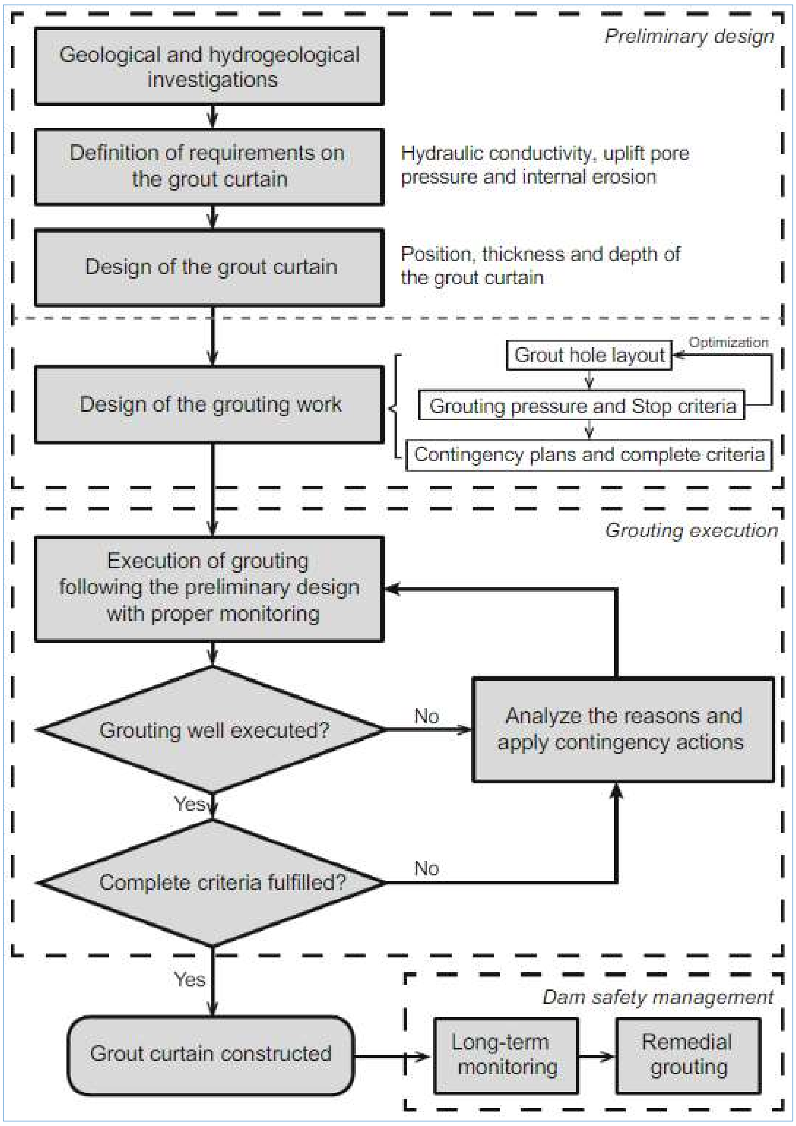

Fig. 2. Flowchart illustrating the principles of the design methodology for grout curtains (Zhang et al., 2022)

Lower Mujip Limestones are massive and classified as impermeable according to Lugeon values and the length of the injection curtain was designed to be socketed into these limestones. After the completion of all curtain injections, core control drilling showed that there was injection inflow into the fracture structures. When pressurized water tests were performed again in these control wells, it was observed that water loss was reduced to acceptable levels.

In Wala Dam catchment area, several relevant studies have been carried out to study the stream flow analysis, sedimentation yield, dam reservoir capacity, rainfall-runoff relationship and components of the surface water (Hadadin, 1992; Zaarir, 1995; Ismail, 1986; AlBalawi, 2003; Ijam and Tarawneh, 2012; Hadadin, 2016; Ijam and AlSaraireh, 2021).

3. Material and Method

3.1. Drilling Water

The water used in this study is the water currently in the dam, which is harmful to cement after the necessary chemical analyzes are made. When it was determined that it did not contain chemical and biological factors, it was used by submersible pumps.

3.2. Cement

Portland cement was used because the sulfate content of the groundwater was at a level that would not harm the cement. It should have a specific surface of at least 2400 cm^2/gr, a residue of at most 1% on a 200-micron sieve and a residue of at most 12% on a 9-micron sieve.

4.2.3. Bentonite

The main task of bentonite to be used in the injection mixture is to keep the cement particles and sand suspended in the mixture. Bentonite to be used should be mixed with water at a ratio of 1/10 and kept for 24 hours before use.

3.4. Additive Material

In cases where it was necessary to accelerate the injection setting time, setting accelerators, viscosity regulators, super plasticizers were used according to the cement ratio calculation with the approval of the administration.

3.5. Sand

Sand proportioned according to the weight of cement was used at the stages where the injection intake was too high. The sand used must be clean and originate from hard, durable stones.

3.6. Mixtures

The material ratios that make up the mixtures prepared for use in injection studies are given in Table 2. As can be seen in Table 2, 5 mixtures were prepared as M3, M4, M5A, M5 550 and M6. Cement, water, sand and bentonite materials were used in the preparation of the mixtures used in the study.

3.7. Curtain Injection Works

The grouting project was prepared according to the technical specifications of the Jordan Ministry of Water. Unless otherwise stated, 24-meter Ano system and decreasing spacing method was applied for curtain injections. Unlike the project, it was decided to change the anode lengths if the injection intake in the wells was different than expected. The new design methodology proposed by Zhang et al. (2022) for grouted bulkheads consisting of three phases: preliminary design, grouting implementation and dam safety management is given in Fig. 2.

3.7.1. Quality Control Experiments on Injection Mixture

Several experiments were conducted to determine the quality control of the injection mix. In this context, setting start and end times of the mixture were determined. Samples made of cement were subjected to compressive strength tests for 7 and 28 days and compressive strength values were determined. Viscosity tests were performed for each type of mixture with the Marsh funnel test apparatus. When deemed necessary, viscosity tests were performed again at the outlet of the injection plant and also before the well was pumped. It was ensured that each mixture complied with the viscosity values determined at the beginning of the project.

Mud scales were used to check that the type of injection used was within the specific gravity limits given at the beginning of the project. Specific gravity tests were performed continuously both at the injection plant outlet and at the wellhead before the start of injection. At the end of 2 hours, it was ensured that the sedimentation value did not exceed 5%.

3.7.2. Drilling Method

Injection and control wells were drilled with a rotary system with water. The wells inside the tunnel were drilled with an electric motor drilling rig and the wells outside the tunnel were drilled with a diesel engine rig. Wells at the anode heads (A wells) were drilled with core and intermediate wells were drilled without core (melt). Intermediate wells were also core drilled when injection uptake was different than expected. Pressurized water tests were performed on the core wells to determine the water permeability capacity of the rocks. Pressurized water test bars were made in the form of 0-3-5-10-5-3-3-0, each stage for 3 minutes. Clean water was used in drilling, circulating water was discharged from the drilling area. After the well drilling was completed, the well was flushed with pressurized water before injection to prevent the cavities from filling with crushed material.

3.7.3. Determination of Curtain Injection Depths

In dam projects, the depth of the curtain injection is determined by classifying the permeability of the rocks as a result of pressurized and unpressurized water tests. If the impermeable rock is not very deep, it is most preferred to construct the grouting curtain up to this rock. In Wala Dam, Lower Mujip Limestones, which are considered impermeable according to Lugeon values, are at an average depth of 90-100 meters, so the injection curtain was designed to this depth.

3.7.4. Determination of Curtain Injection Drill Intervals

Curtain grouting drilling and grouting works are done with an anode system. The length of an anode can be 6-12-24 meters. Before the drilling and injection works in one anode are completed, the other anode is not started. In order to determine the length of the anodes and the distance between the wells, test drilling and injection works are carried out in a small-scale area representing the geological and structural features (fractures, cracks, voids) in the project area. According to the results, the distance between drill holes and anode lengths are determined (Özkan, 2006).

Ano lengths were determined as 24 meters at Wala Dam (Fig. 3). Primary boreholes at the beginning and end of the Ano were core drilled and pressurized water test was performed. In the primary, secondary, tertiary, quaternary and even in the sections with multiple injection intake, injection holes were drilled again by entering between the completed wells, the distance between these holes was reduced to 0.50 meters. Coloring should be done according to the injection amount/meter used in the injection.

3.7.5. Determination of Shear Injection Pressures

The recommended pressures for curtain grouting are as follows (Özkan, 2006)

PT= 0.33H (this pressure in the last two phases of 2.5 meters)

PT= 0.23H is recommended.

PT: Total effective pressure (kg/cm^2)

H: Distance from the center point of the injection stage to the spout (m).

3.7.6. Injection Applications

The injection was carried out by drilling the well completely and then injecting from bottom to top (ascending stages). In cases such as water loss of more than 70% during drilling progress, inability to make progress due to demolition, drilling was stopped and the well was injected with the descending stage injection method, and after setting, the well was re-drilled to secure the well and prevent water leaks.

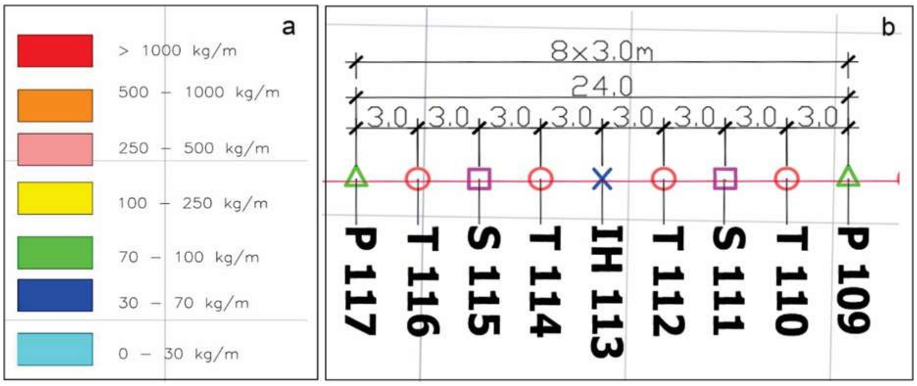

Fig. 3. Injection Reception Scale (kg/m) and 24-meter injection drilling sequence in Ano

Table 3. Depth dependent effective pressure values to be applied depending on the depth in the stage to provide the refuge condition in vertical wells at Wala Dam

Stage (m)	L (m)	Effective Refusal Pressure of stage for grout (P_{eff})
0-5	2.50	3.0
5-10	7.50	4.5
10-15	12.50	6.0
15-20	17.50	7.5
20-25	22.50	9.0
25-30	27.50	10.5
30-35	32.50	12.0
35-40	37.50	13.5
40-45	42.50	15.0
45-50	47.50	16.5
50-55	52.50	18.0
55-60	57.50	19.5
60-65	62.50	21.0
65-70	67.50	22.5
70-75	72.50	24.0
75-80	77.50	25.5
80-85	82.50	27.0
85-90	87.50	28.5
90-95	92.50	30.0
95-100	97.50	31.5
100-105	102.50	33.0
105-110	107.50	34.5
110-115	112.50	36.0
115-120	117.50	37.5
120-125	122.50	39.0
125-130	127.50	40.5
130-135	132.50	42.0
135-140	137.50	43.5
140-145	142.50	45.0
145-150	147.50	46.5
150-155	152.50	48,0
155-160	157.50	49,5
160-165	162.50	51.0
165-170	167.50	52.5
170-175	172.50	54.0
175-180	177.50	55.5
180-185	182.50	57.0

Injection works were started with M3 mixture. If no pressure increase is observed in the pressure gauge despite the amount of injection specified in the project, the next mixture is started. From the mixture with low density to the mixture with high density, it is ensured that the well is saturated with injection (refu) by using the amounts determined at the beginning of the project.

Mixture ratios and quantities used are recorded. If the desired stage pressure is obtained as a result of the injection mixture used and there is no injection intake within 10 minutes, the well is returned to the initial mixture first given in the well and if there is an injection intake of 0.6 liters/meter/minute or less within 20 minutes in the injection stage, the stage is refluxed (for example, 3 liters/minute for 5 meters injection stage). Table 4 effective pressure values to be applied depending on the depth of the stage to provide the refuge condition in vertical wells at Wala Dam are given in Table 4.

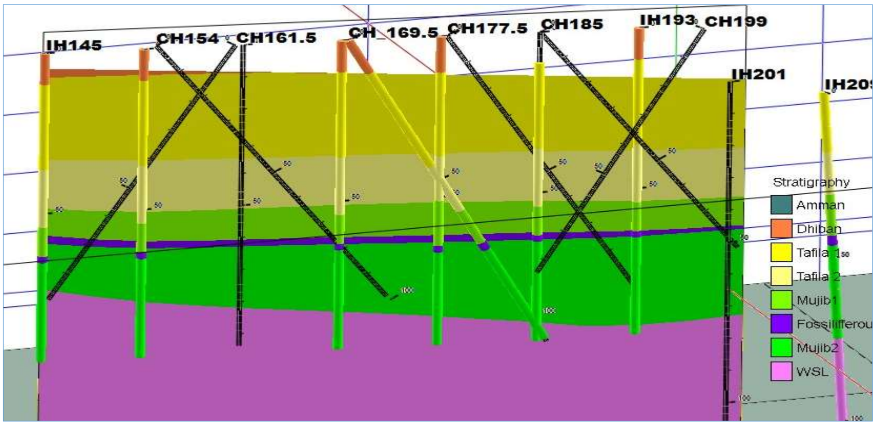

Fig. 4. Cross Section of Inclined Control Wells Cutting Injection Wells

Fig. 5. Digital inclinometer device measuring borehole inclination

4. Results and Discussion

4.1. Core Control Drilling

After the injection is completed in all wells planned in an anode and, if deemed necessary, in additional wells, a control well with core is drilled on the same axis with a slope to cut the maximum well (Fig. 4). Core samples are taken from the drilled well and visual inspection is performed with the help of a loop to check whether the fracture and crack systems are filled with injection. To ensure that the slope of the well does not deviate from the value given in the project, it should be controlled with an inclinometer device (Fig. 5).

4.2. Control with Pressurized Water Test

Control well CH-52 of Wala Dam was drilled and pressurized water tests were carried out at 35.00-40.00 m, 58.00-63.00 m, 69.00-74.00 m and 82.00-87.00 m interval levels of the well. With the help of the results obtained, Lugeon graphs were drawn, and it was checked whether the impermeability was achieved at the mentioned levels of the control well (Figs. 6-9).

Pressurized water tests were carried out at different stages in the control well CH-52 of Wala Dam. According to the results obtained, water intake increases as the pressure increases between 35.00-40.00 meters and decreases again when the pressure decreases. When this situation is followed in the graph, it indicates that the filling material in the cracks due to pressure is cleaned or there is a leakage in the test tire (Fig. 6). As a result, it can be said that impermeability is not achieved at the desired level in this control well .

The pressurized water test results of Wala Dam between 58.00-63.00 meters are given in Fig. 7. As can be seen in the figure, it is seen from the test results that the water leakage remains constant despite the increase in pressure. In the evaluation of the graph, it is observed that the cracks are plugged at low pressure and the cracks are cleaned at high pressure. Considering the Lugeon value (0.2), it is accepted that impermeability is achieved (Fig. 7). The results of the pressurized water test at the level between 69.00-74.00 meters of the control well CH-52 of Wala Dam are given in Fig. 8.

According to the test results, it is seen that the water leakage remains constant although the test pressures increase. In this case, considering the Lugeon value (0.2), it is accepted that impermeability is ensured (Fig. 8).

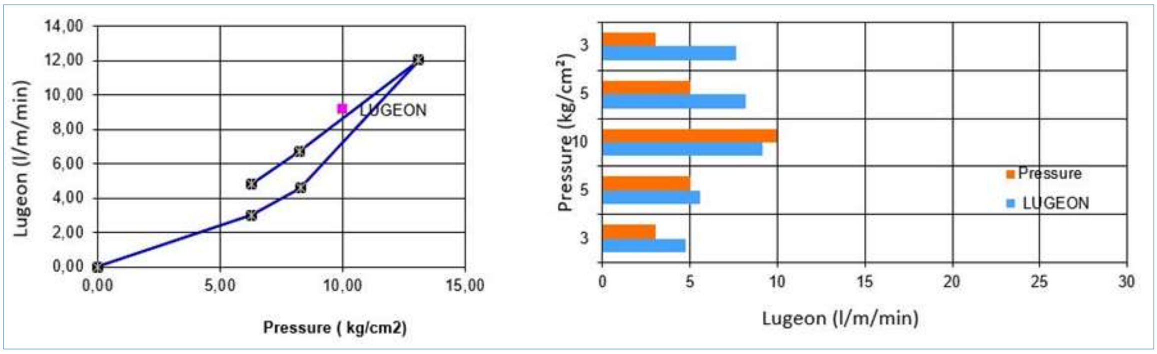

Fig. 6. Lugeon graph of Pressurized Water Test results of CH-52 well between 35,00-40,00 m (Lugeon 9,1)

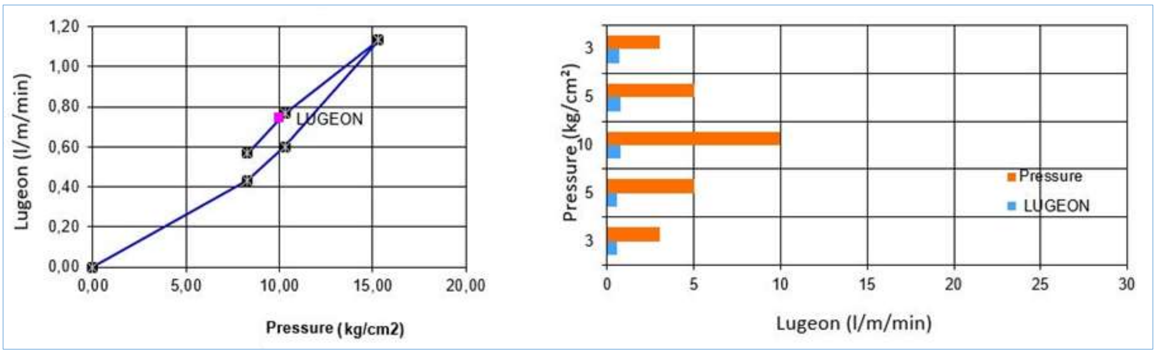

Fig. 7. Lugeon graph of CH-52 well 58,00-63,00 m Pressurized Water Test results (Lugeon 0,7)

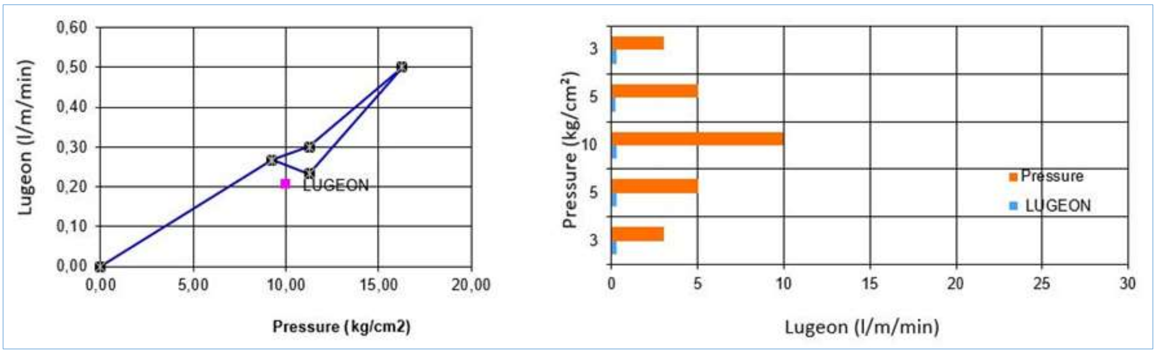

Fig. 8. Lugeon graph of CH-52 well 69,00-74,00 m Pressurized Water Test results (Lugeon 0,2)

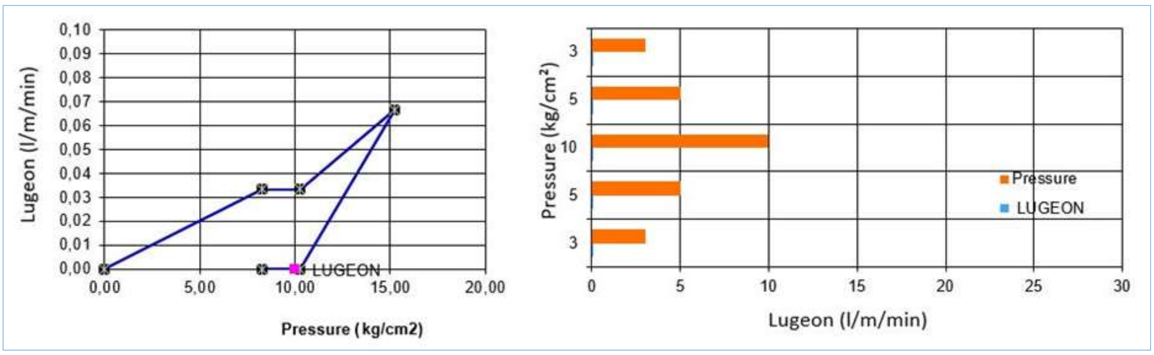

Fig. 9. Lugeon graph of CH-52 well Pressurized Water Test results between 82.00-87.00 m (Lugeon 0.1)

The results of the pressurized water test at the level of Wala Dam between 82.00-87.00 meters are given in Fig. 9. According to the test results, it is seen that the water leakage remains constant although the test pressures increase. In this case, the Lugeon value (0.1) is also taken into consideration, and it is accepted that impermeability is achieved (Fig. 9).

5. Conclusion

As a result of the Wala Dam body elevation project, the reinforced concrete body was raised by 15 meters, reaching a body height of 65 meters. As the water retention capacity of the dam increases because of raising the dam body, the water load on the right and left banks will increase. For this reason, creating an impermeable curtain is critical in minimizing water leaks. As a result of the curtain injection works carried out in Wala Dam, impermeability was achieved. Although the length of the injection curtain is generally calculated according to the dam body length during the curtain injection project design phase, the injection curtains were designed and implemented to be inserted into this formation, as the Lower Mujip Limestone, which is considered impermeable according to Lugeon values, in the valley where the Wala Dam was built, is at an average depth of 90-100 meters. . It was determined that impermeability was achieved thanks to the core test wells and pressurized water tests.

Conflict of Interest

The authors declares that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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