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EVALUATION OF ANTI-SEEPAGE QUALITY FOR THE PAC MA HYDROPOWER DAM FOUNDATION USING GROUTING METHOD

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ABSTRACT: The Pac Ma Hydropower Project is constructed on a dam foundation characterized by fractured porous rock and complex geological and hydrogeological conditions, resulting in a high risk of seepage within the foundation zone. This paper presents an assessment of anti-seepage performance through staged curtain grouting using cement slurry and bentonite mortar incorporating sodium silicate. Based on engineering geological investigations and Vietnamese standards, six reinforcing rows and three curtain rows were installed with a treatment depth of 10.5 m and borehole spacing of 0.75–1.0 m. Field permeability was evaluated using Lugeon water pressure tests before and after grouting. Before large-scale construction, experimental grouting was conducted in four stages with different grout materials and borehole layouts to determine technical parameters. The results showed that only the dense borehole configuration combined with cement–bentonite–sodium silicate mortar achieved the required permeability reduction. The initial permeability ranged from 26 to 50 Lu (approximately 2.6×10^{-6} to 5.0×10^{-6} m/s). After treatment, Lugeon values in 25 boreholes decreased to 1.14–4.88 Lu (approximately 1.1×10^{-7} to 4.9×10^{-7} m/s), all below the 5 Lu design requirement. These results confirm that fractures and voids were effectively sealed, forming a continuous grout curtain beneath the dam. The near one-order-of-magnitude reduction in hydraulic conductivity demonstrates the efficiency of the optimized multi-row system under fracture-controlled conditions. The findings also provide quantitative documentation of the tectonic structure, U-shaped valley morphology, and fracture network of the Da River basin, highlighting its geological significance alongside engineering implications.

Keywords: Seepage, Fractured porous rock, Lugeon value, Grouting method, Hydropower dam

1. INTRODUCTION

Dams are hydraulic structures constructed across rivers to control upstream water levels and regulate water flow for purposes such as hydropower generation, irrigation, and flood control. Hydropower remains the most economical, clean, and renewable traditional energy source, contributing significantly to socio-economic development and energy security in many countries, including Vietnam [1]. However, the safety and long-term stability of these structures depend largely on effective seepage control. Seepage, defined as the movement of water from the upstream to the downstream side through the dam body or foundation, may lead to uplift pressure, internal erosion, and progressive weakening of the dam foundation if not properly controlled [2]. Excessive hydraulic gradients may approach the critical hydraulic gradient of dam foundation materials, potentially triggering piping or internal instability when effective stress is significantly reduced. Therefore, ensuring the safety of dams requires reliable hydrological and geotechnical investigations as well as appropriate seepage control measures. In addition, practical protective solutions, such as erosion-resistant layers and structural protection systems, have been widely applied to reduce damage under severe hydraulic and hydrological conditions [3].

In many cases, seepage complications in fractured rock masses represent a significant concern in hydraulic engineering. Complex geological conditions, such as faults and fracture networks, often lead to abnormal leakage rates in hydropower dam foundations [4]. Fractures and cracks tend to increase the permeability and porosity of rock masses, providing preferential flow paths for groundwater. Statistics indicate that more than 90% of water inrush and leakage-related incidents in underground engineering are associated with geological fractures and faults, highlighting the critical role of discontinuities in controlling groundwater flow [5]. The presence of deep surface cracks can facilitate rapid water seepage into subsurface layers, significantly increasing hydraulic conductivity compared with intact materials [6]. Furthermore, under reservoir pressure, existing cracks may be widened by water pressure, a phenomenon known as hydraulic fracturing, resulting in concentrated leakage and further increasing dam foundation permeability [7]. In fractured porous rock foundations, seepage is predominantly governed by fracture connectivity, aperture, and spacing rather than by intact rock matrix permeability, making fracture-targeted treatment essential. Among the available grouting materials, cement slurry remains the most widely used due to its availability and cost-effectiveness. In fractured porous rock conditions, cement–bentonite mixtures are often preferred because bentonite improves stability, reduces bleeding, and enhances suspension performance. The incorporation of sodium silicate can further accelerate gel formation and improve penetration into fine fractures, thereby increasing sealing efficiency in fault-controlled permeability zones [8]. Therefore, continuous monitoring and calibration of the hydraulic and mechanical properties of dam materials are necessary to assess seepage risks in large-scale hydropower projects properly [9]. Despite its widespread application in dam engineering, the quantitative performance of staged multi-row curtain grouting systems under fracture-controlled hydrogeological conditions remains inadequately quantified. Most existing studies emphasize numerical simulations or laboratory-scale experiments, whereas comprehensive field-based evaluations integrating parameter optimization and post-grouting permeability verification remain limited. Consequently, systematic field-scale validation of permeability reduction efficiency in highly fractured, fault-controlled dam foundations are still lacking.

To mitigate these risks, foundation treatment is required to seal fractures and hollow zones within the rock mass. Curtain grouting is considered a key technique for controlling water seepage in dam foundations, particularly in fractured rock environments where discontinuities form preferential flow paths [9]. This method involves injecting fluid grout mixtures into pores and joints to improve the physical and hydraulic properties of the foundation. Among the available materials, cement slurry is commonly preferred due to its abundant availability, low cost, and effectiveness in filling fractures and preventing environmental contamination caused by leakage [5]. Cement–bentonite mixtures are increasingly adopted due to their improved stability, reduced bleeding, and enhanced suspension characteristics, while sodium silicate additives can accelerate gel formation and improve penetration into fine fractures. The performance of a grout curtain is typically evaluated based on its ability to reduce uplift pressures and control seepage through the foundation. Practical applications have demonstrated that integrated seepage control systems, combining grout curtains and drainage hole arrays, can significantly lower groundwater levels even under complex geological conditions [11].

In Vietnam, small and medium-sized hydropower projects have contributed significantly to the national power grid. However, uncontrolled seepage remains a major concern, particularly in structures constructed under complex geological conditions. Several incidents related to seepage and foundation treatment have been reported, including the failure of downstream slopes at dams such as Trieu Thuong No. 2, where differences in hydraulic conductivity between old and new fill materials and the presence of undetected soft soil layers led to instability [12]. Although grouting was first applied on a large scale during the construction of the Hoa Binh Hydropower Project in 1979, and technical standards for drilling and cement grouting into rock foundations have since been developed and widely implemented, practical experience has shown that grouting works are not always successful. Problems associated with seepage and foundation treatment have been observed at structures such as the Nam Thach Han spillway, Phu Ninh Dam, Vuc Tron Dam, and Thanh Long Dam, particularly under complex geological conditions [13, 14]. This situation highlights a practical engineering problem: how to optimize grout composition, borehole spacing, and injection sequencing to achieve reliable seepage reduction in fractured porous rock foundations characterized by fault-controlled permeability. However, existing studies rarely integrate grout material selection, staged injection control, and dense borehole network design within a unified quantitative evaluation framework, leaving uncertainties in practical optimization strategies.

The Pac Ma Hydropower Project is located in an area characterized by fractured porous rock affected by fault zones, resulting in a high risk of seepage through the dam foundation. The foundation mainly consists of highly weathered and jointed rock masses, where fractured networks and weak zones form preferential paths for groundwater flow. The heterogeneity of the rock mass, the presence of fault-related structures, and the strong hydraulic connection with the Da River create geological conditions that differ from relatively intact rock foundations commonly reported in previous grouting case studies. These geological characteristics increase the uncertainty in seepage prediction and control, making foundation treatment design more complicated than in relatively intact rock environments. Such complex conditions require not only an appropriate treatment solution but also a systematic and quantitative evaluation of seepage control effectiveness to ensure long-term structural safety. In particular, the relatively high initial permeability and the strong hydraulic interaction between the fractured foundation and the Da River distinguish the Pac Ma site from previously reported case studies conducted in more homogeneous or moderately fractured rock masses.

Therefore, this study aims to provide a quantitative field-based assessment of the anti-seepage performance of the dam foundation of the Pac Ma Hydropower Plant using a grouting method with cement slurry and bentonite mortar incorporating a sodium silicate additive. The evaluation was conducted through staged curtain grouting combined with pre- and post-grouting water pressure (Lugeon) tests to quantify changes in hydraulic conductivity and assess improvement efficiency. The selected grouting system offers several practical advantages, including simple construction procedures, high reinforcement efficiency [15]. This method has been successfully applied in several hydropower projects in Vietnam, demonstrating its effectiveness under similar geological conditions. As the construction of large hydropower dams often causes permanent alterations to the geological surface, the fault characteristics and fracture networks at the Pac Ma site were studied to ensure effective seepage control and preserve the scientific records of an important geoheritage in Northwest Vietnam. The novelty of this study lies in the integration of staged multi-row grouting optimization with dense borehole network design and quantitative permeability verification under fault-controlled fractured porous rock conditions. In addition to its engineering contribution, the systematically documented geological structures, fracture systems, and hydrogeological responses before and after grouting provide a field-based case that may support academic analysis in engineering geology and geoheritage-related studies.

This paper is structured as follows: Section 2 outlines the research significance; Section 3 describes the geological conditions of the Pac Ma project; Section 4 details the grouting design and experimental stages; Section 5 evaluates the results through water pressure tests; and Section 6 provides the conclusions.

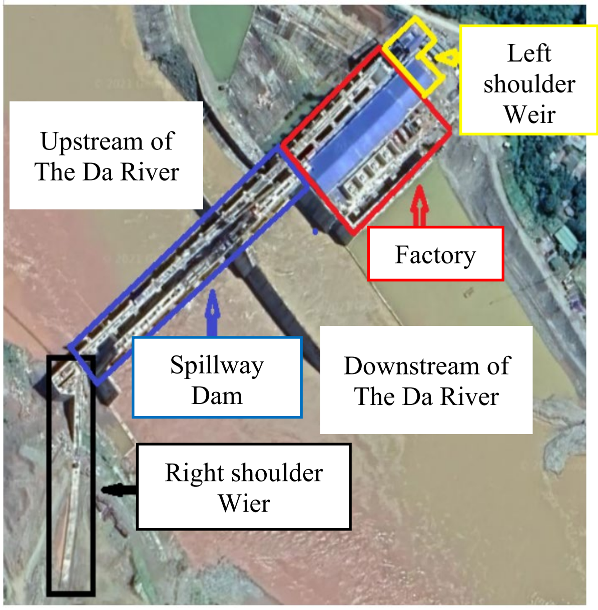

Fig. 1 The area of the Pac Ma Hydropower Project

2. RESEARCH SIGNIFICANCE

Hydropower dams in Vietnam are often constructed in mountainous areas with complex geological conditions. Fractured porous rock foundations can increase the risk of seepage and instability. In such situations, it is important to carefully evaluate how well grouting solutions work based on field performance data. This study investigates the anti-seepage effectiveness of a cement-bentonite grouting method that uses a sodium silicate additive at the Pac Ma Hydropower Project through analysis of in situ water pressure test results. The findings provide valuable data and a technical foundation for using similar solutions in dam foundations with comparable geological conditions.

3. GEOLOGICAL ENGINEERING CONDITIONS

3.1 The Topography and Geomorphology

The dam site is located within a U-shaped river valley, with natural slopes ranging from 20° to 45°. The right bank has elevations varying from approximately +310.0 m to +340.0 m and is characterized by steep slopes and locally developed cliff faces. The weathering crust in the area is unevenly developed, reflecting variations in lithology and structural conditions. The eluvial–deluvial layer (edQ) and the intensely weathered zone (IA1) show variable thicknesses, ranging from about 1.0 m to 20.0 m across the site. In the area between the dam axis and the spillway, the surface geology is dominated by alluvial deposits consisting mainly of boulders, gravel, and sand. These coarse-grained deposits exhibit relatively high permeability and may serve as potential seepage pathways if not properly treated during foundation preparation. These geomorphological and topographic conditions form a relatively stable natural foundation surface and are generally favorable for the layout and construction of the dam and associated hydraulic structures, as shown in Figure 1, which illustrates the valley geometry, slope configuration, and dam axis location. The U – shaped valley morphology, steep slopes, and exposed rock faces reflect long- term fluvial incision and tectonic control, representing characteristics geological - geomorphological features of the Pac Ma area with scientific and educational significance. From an engineering perspective, the steep abutments and strong river incision increase hydraulic gradients during reservoir impoundment, thereby elevating the potential risk of concentrated seepage along structural discontinuities.

3.2 Stratigraphic Characteristics, Physico - mechanical Properties of Soil and Rocks

According to the results of the engineering geological survey of Power Engineering Consulting Joint Stock Company 1 (see Figure 2 for the geotechnical cross-section along the right dam axis), the stratigraphy is divided into five zones as follows:

Zone 1 (apQ, aQ): Composed of yellowish grey, brown, greyish brown, sandy clay, clayey sand mixed with gravel. The thickness varied from 2 m to 15 m. Due to its loose structure and relatively high porosity, this zone may facilitate shallow groundwater flow.

Zone IA1: Composed of grey, greyish brown, yellowish grey, clay, sandy clay with 12÷20% gravel. The thickness changes from 2 to 12 m. This zone represents an intensely weathered layer with reduced strength and moderate permeability.

Zone IA2 (Intensive weathered zone): Composed of gravel with clay and sandy clay. The thickness changes from 2 to 6 m. The presence of gravel lenses increases local permeability heterogeneity.

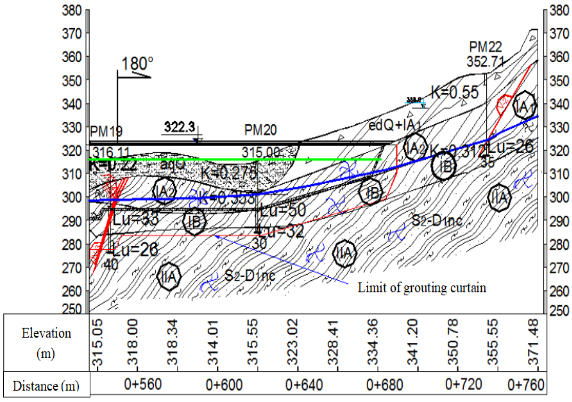

Fig. 2 Geotechnical section of the right dam

Zone IB (Medium weathered zone): composed of medium weathered rock with cracks. Some cracks were filled with clay and gravel. The thickness varied from 3 to 15 m. Open and partially filled fractures in this zone significantly influence seepage behavior and grout penetration efficiency.

Zone IIA (Slightly weathered zone): composed of shale, sericite shale sandwiched with thin layers of gray, blue-grey, strongly fractured sandstone. Although the intact rock matrix exhibits relatively low intrinsic permeability, interconnected fractures form the dominant seepage channels.

The physico-mechanical properties of these soils and rocks are shown in Table 1. These parameters provide the quantitative basis for evaluating permeability contrast, deformation characteristics, and the necessity of fracture-targeted seepage control measures.

The vertical stratigraphic characteristics record long-term geological processes and constitute an important scientific basis for interpreting the geological history of the region.

Based on the engineering geological characteristics of the soils and rocks, the dam foundation is classified as a fractured porous rock foundation in accordance with TCVN 8645:2019 [16]. This classification reflects the widespread development of fractures, joints, and weathered zones within the foundation rock mass, which directly controls groundwater flow patterns and hydraulic conductivity distribution.

Field investigations indicate that the rock mass in Zones IB and IIA is characterized by joint spacing ranging from approximately 0.10 m to 0.50 m in highly fractured sections and 0.50 m to 1.50 m in moderately fractured sections, with joint apertures generally varying from 0.5 mm to 5 mm. The Rock Quality Designation (RQD) values range from 35% to 70%, corresponding to fair to poor rock quality, and the estimated Rock Mass Rating (RMR) ranges between 40 and 60, indicating a moderately fractured rock mass. Such structural conditions promote fracture-controlled seepage rather than matrix-dominated flow.

From a tectonic perspective, two grade IV faults are identified within the dam construction area. The faults and fracture systems represent typical geological structures that significantly influence the permeability behavior of the dam foundation. These fault zones are associated with increased fracturing and permeability and are considered major factors contributing to water loss through the dam foundation. The spatial distribution of these faults is indicated in Fig.2 and is further considered in the grout curtain layout design.

In the present case, seepage is predominantly controlled by fracture flow rather than matrix permeability, as indicated by the relatively high Lugeon values (26–50 Lu) measured in the slightly to moderately weathered zones. The intact rock matrix exhibits comparatively low intrinsic permeability, whereas interconnected discontinuities form preferential flow paths governing the hydraulic behavior of the dam foundation. This hydrogeological behavior justifies the adoption of a staged multi-row grout curtain system targeting fracture connectivity rather than uniform matrix treatment.

Regarding hydrogeological characteristics, the depth of the groundwater table shows considerable spatial variation across the project area. Groundwater is actively developed in cohesionless alluvial deposits, where boulders, gravels, and sand provide favorable conditions for water movement. In the weathered rock zones, the groundwater level is generally close to the river water level, indicating a strong hydraulic connection between surface water and subsurface flow. During the dry season, the groundwater depth typically ranges from 5.5 m to 15.0 m. In areas adjacent to the dam abutments, the groundwater level commonly varies between elevations of approximately +301.0 m and +310.5 m, which is lower than the normal reservoir water level of +316.0 m. This difference in hydraulic head creates conditions favorable for seepage through the dam foundation and highlights the necessity of appropriate anti-seepage treatment measures. This hydraulic head difference generates significant seepage gradients toward the downstream side after reservoir impoundment, increasing the risk of uplift pressure and internal erosion along fractured zones. Therefore, systematic permeability reduction through grout curtain construction is required to ensure foundation stability.

The depth of the grout curtain was determined based on the vertical distribution of permeability obtained from borehole water pressure tests and the requirement that the treated zone extend beyond the highly fractured and weathered strata into relatively less permeable rock layers. This selection was verified by staged grouting and follow-up Lugeon testing rather than by classical flow net analysis, due to the discontinuous and fracture-dominated hydraulic regime of the dam foundation.

Table 1. The physico -mechanical properties of soils and rocks

Physico-mechanical properties	Zone IA1 & IA2	Zone IB	Zone IIA
Natural water content, %	23		
Specific gravity	2.74	2.74	2.77
Void ratio, e	0.851		
Natural unit weight, kN/m^3	17.75	24.33	27.47
Saturated unit weight, kN/m^3		24.82	27.56
Dry unit weight, kN/m^3	14.41		
Saturated internal friction angle, Degree	14÷16		
Saturated cohesion, MPa	0.022		
Deformation modulus, MPa	10.79		
Elastic modulus, MPa		936÷1963	4413-8826
Saturated stability coefficient		1.9	4.8
Dry-wind sustainability coefficient		3.4	5.3
Saturated compressive strength, MPa		18.53	32.76
Dry compressive strength, MPa		18.82	37.75
Saturated tensile strength, MPa		1.76	3.23
Dry tensile strength, MPa		1.96	3.72
Permeability coefficient, m/day	0.120÷0.353		
Lugeon value, Lu		26÷50	26÷35

4. DESIGN THE GROUTING METHOD

The process of grouting was arranged in three steps: design, experimental testing, and grouting.

At the design stage, the grouting layout was developed similarly to other projects such as Son La, Rao Quan, and Huoi Quang dams. The grouting holes were arranged at 3m intervals with a final depth of 5.0 m for the reinforcing rows, according to the geological engineering conditions (TCVN 8645: 2019, TCVN 9137:2021) [16, 17]. The total number of grouting rows was seven. In addition, a primary waterproof grout curtain was arranged at 3.0 m spacing with a final depth of 10.0–10.5 m. Otherwise, the waterproof grouting was also arranged at 3 intervals with 10.0m final depth. The row of waterproof grouting was one. The angle of the grouting borehole was 90° relative to the horizontal plane (vertical boreholes). The selection of the grout curtain depth (10.0–10.5 m) was based on the vertical distribution of Lugeon values obtained from borehole water pressure tests, ensuring that the curtain penetrated through the highly fractured and weathered zones (Zones IB and upper IIA) into relatively less permeable strata. The grouting pressure changed from 0.3 MPa to 0.5 MPa according to the depth and the geological conditions. Considering an average unit weight of 24-26 kN/m³, the vertical overburden stress at a depth of 10 m is approximately 0.24-0.26 MPa. Although the maximum applied injection pressure reached 0.5 MPa, fracture initiation pressure in fractured rock masses is typically higher than the vertical stress due to lateral confinement and the tensile strength of intact rock bridges. The injection pressure was increased stepwise during grouting operations, and no evidence of hydraulic fracturing, surface heave, or abnormal grout take was observed. The total grouting volume was adjusted according to the results of the experimental grouting stage. The experimental grouting area is shown in Fig. 3, Fig.4. The equipment for grouting is shown in Fig. 5.

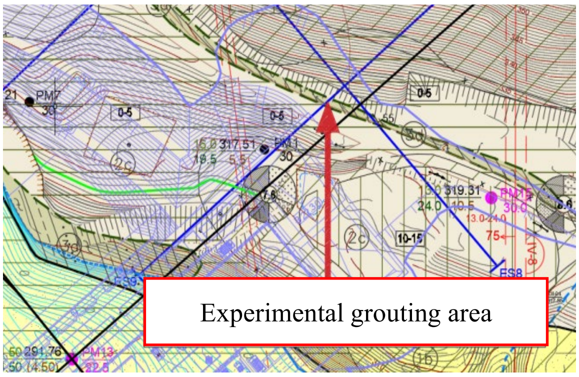

Fig. 3 Diagram of experimental grouting area

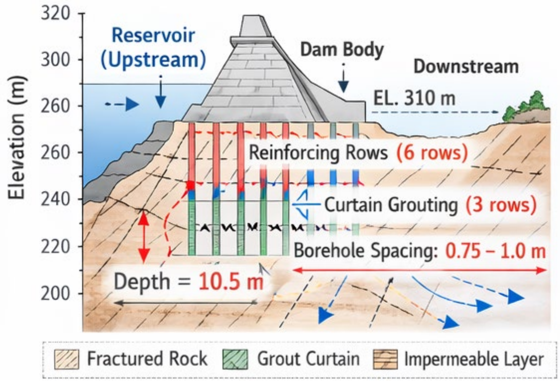

Fig. 4. Diagram of experimental grouting

In the experimental grouting step, there are four different stages. In which stage, the process of grouting includes: drilling, washing, water pressure test, grouting, and water pressure test. The properties of each stage are shown in Table 1.

Table 2. The properties of the experimental grouting step

Experimental stage	1	2	3	4
Type of solution for grouting	Cement and water			Bentonite added sodium silicate additive
Grouting rows for the curtain	1	2	2	3
Grouting network	3.0x3.0 m	2.0x3.0 m	2.0x1.5 m	1.0x0.75 m

As shown in Table 2, it can be seen that in stages 1÷3, the grouting method for the curtain did not succeed. The Lugeon value after treatment was not less than 5 Lu. Secondary and tertiary grouting were therefore implemented in Stage 4 to further reduce permeability to the design requirement of ≤5 Lu. Only the fact that the properties of grouting for curtain in stage 4 were used in this project to reduce the seepage in the dam. The number of grouting rows for the curtain was three. The grouting distance of each row was 1.0 m, and the distance between two grouting holes was 0.75 m. This network is used for the grouting step.

Fig. 5 The equipment for grouting

The grouting depth was 10.5 m (Fig.5), with the angle of the grouting hole being 90^0 compared to the horizontal direction.

At the grouting step, the construction sequence is as follows:

Grouting cement mortar for reinforcing rows: The grouting rows were six, with the depth of the grouting borehole of 5.0 m. The grouting hole angle was 90^0 relative the horizontal direction. The grouting pressure changed from 0.15 MPa to 0.3 MPa. The grouting work in the borehole ended after maintaining the maximum grouting pressure for 15 minutes, when the consumption was reduced to less than 1 liter per min.

Grouting for Curtain: There were 03 rows of grouting boreholes along the center of the dam. The rows 1 and 2 were located at the center of the line of the dam and downstream of the dam. The solution for these grouting boreholes was cement slurry and water. The ratios of cement and water were 1:10, 1:8, 1:5, 1:3, 1:2, 1:1, respectively. Row 3 was located between row of the dam center and downstream, which is grouted with bentonite and water, with sodium silicate additive. The sodium silicate equaled 4% by weight of bentonite. The ratio of bentonite and water was 1:10, 1:8, 1:5, 1:3, 1:2, 1:1, respectively. The incorporation of sodium silicate was intended to enhance gel formation and improve sealing efficiency in fine fractures where cement slurry penetration alone was insufficient.

The grouting process was started with the borehole of row 2. Then, the boreholes of row 1 were performed. Finally, boreholes of row 3 were constructed.

After grouting, the boreholes of rows 1 and 2 were rested for 4 hours. In each section of the grouting boreholes in rows 1 and 2, the rest time was not smaller than 4 hours. However, the rest time for grouting boreholes in two rows was also not shorter than 4 hours.

In the boreholes of row 3, the rest time for each section was zero.

The grouting pressure changed for each section. For the first section from 0.0 to 5.0 m, the grouting pressure was 0.30 MPa. In the next section, from 5.0 to 10.0 m, the grouting pressure was 0.50 MPa.

The grouting was finished when the maximum grouting pressure was maintained 15 minutes, the grout absorption flow was smaller than 0.2 liters per minute per square meter.

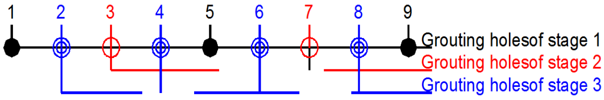

Fig. 6. Order of grouting per row

In each row, the order of grouting sessions is shown in Figure 6. After the grouting was finished, the boreholes were immediately filled with cement and water with the ratio of 0.5:1 or cement and sand with the ratio of 1:1.

5. EVALUATION OF THE QUALITY OF GROUTING METHOD

There are several methods commonly used to evaluate the quality of grouting works, including water pressure testing, core sampling from boreholes combined with laboratory testing, and in situ permeability assessment. Laboratory tests usually focus on determining compressive strength and permeability of core specimens taken from the grouted zones. However, these methods are limited in reflecting the overall sealing performance of the grout curtain at the field scale, particularly in fractured rock masses where seepage is predominantly governed by discontinuity-controlled flow rather than matrix permeability. For this reason, the water pressure test was selected as the primary method to evaluate the quality of the anti-seepage treatment for the Pac Ma Hydropower Project, as it allows direct assessment of permeability reduction within the treated foundation.

In order to obtain an accurate evaluation, the water pressure test was used for this project (Fig. 6). The test was carried out 4 days after the completion of the mass anti-seepage step, allowing sufficient initial curing time for cement hydration and sodium silicate gel stabilization under groundwater conditions. Testing boreholes were evenly distributed throughout the dam route. The depth of the boreholes to perform the water pressure test was equal to the depth of grouting. Each section to test changed from 5.0 to 5.5 m according to TCVN 8645:2019 [16]. The total test length of boreholes was taken as equal to 7% of the total length of grouting boreholes. The water pressure test included 3 pressure levels. The maximum pressure equaled to 70÷80% of the maximum grouting pressure in the adjacent boreholes and 2 levels of recovery pressure (BS 5930:2015) [18], in order to avoid hydraulic fracturing and ensure that the applied test pressure remained lower than the estimated in situ overburden stress at corresponding depths. The experimental results are presented in Table 3.

Fig. 6 The water pressure test

As shown in Table 3, the following observations can be drawn:

The applied water pressure levels during testing ranged from 0.23 to 0.41 MPa. The length of each tested section was 5.0 m or 5.5 m, corresponding to the grouting depth. Under these test conditions, the measured Lugeon values varied from 1.14 to 4.88, reflecting a significant reduction in permeability within the treated dam foundation zone. A total of 50 post-grouting Lugeon test sections were analyzed. The measured values ranged from 1.14 to 4.88 Lu, with an average value of 2.55 Lu and a standard deviation of 0.90 Lu. The relatively low standard deviation indicates a uniform permeability distribution after grouting treatment. For comparison, the initial Lugeon values of the foundation rock mass ranged from 26 to 50 Lu prior to treatment. These Lugeon values correspond to an equivalent permeability coefficient ranging from approximately 1.14×10^{-7} to 4.88×10^{-7} m/s, compared to the initial permeability of approximately 5.0×10^{-6} to 2.6×10^{-6} m/s prior to treatment. This represents an overall permeability reduction of approximately one order of magnitude, indicating a substantial improvement in hydraulic performance after grouting.

Spatial analysis shows that mean Lugeon values vary between 1.88 Lu and 4.21 Lu across different borehole rows. Lower values were observed in rows KTB3 and KTB5, indicating more effective permeability reduction, whereas slightly higher values in KTB1 and KTB6 may reflect locally persistent fractured connectivity. However, all mean values remain below 5 Lu, satisfying commonly accepted dam foundation seepage control criteria.

All tested sections recorded Lugeon values lower than 5, which meets the acceptance criteria specified in ВН ИИГ П21-85. This result indicates that cracks, joints, and voids within the grouting influence range were adequately filled by the injected grout materials. The proportion of test sections satisfying the flow loss unit requirement was 100%, demonstrating uniform seepage control performance across the dam foundation. No test section exhibited residual permeability greater than 5 Lu prior to acceptance, indicating that secondary grouting was not required after the final curtain configuration was implemented.

The grouting work resulted in the formation of a continuous grout curtain along the dam axis. This grout curtain, in combination with the concrete dam structure, forms an integrated seepage control system beneath the dam. In the bedrock zones, the curtain contributes to extending the seepage path, reducing seepage pressure, and lowering the hydraulic gradient, thereby improving the overall impermeability of the dam foundation, with seepage flow primarily controlled through fracture sealing and connectivity reduction within the treated zone.

Table 3. Tested results of water pressure test at 25 boreholes

No	**Name of borehole**		**Depth, m**	**Water pressure p_{max} MPa**	**Lugeon value, q, Lu**
1	KTB1-1	section 1	5.0	0.225	3.94
		section 2	5.0	0.343	4.48
2	KTB2-1	section 1	5.0	0.225	2.76
		section 2	5.0	0.343	3.41
3	KTB2-2	section 1	5.0	0.225	2.25
		section 2	5.0	0.343	3.19
4	KTB2-3	section 1	5.0	0.225	3.07
		section 2	5.0	0.343	2.93
5	KTB2-4	section 1	5.0	0.225	2.80
		section 2	5.0	0.343	3.10
6	KTB2-5	section 1	5.0	0.225	3.23
		section 2	5.0	0.343	3.26
7	KTB3-1	section 1	5.0	0.255	1,77
		section 2	5.0	0.392	2.40
8	KTB3-2	section 1	5.0	0.245	1.20
		section 2	5.0	0.382	2.55
9	KTB3-3	section 1	5.0	0.245	1.21
		section 2	5.0	0.382	2.56
10	KTB3-4	section 1	5.0	0.245	1.42
		section 2	5.0	0.382	2.80
11	KTB3-5	section 1	5.0	0.255	1.15
		section 2	5.0	0.392	2.90
12	KTB4-1	section 1	5.0	0.265	2.71
		section 2	5.5	0.402	2.61
13	KTB4-2	section 1	5.0	0.265	1.50
		section 2	5.5	0.402	2.16
14	KTB4-3	section 1	5.0	0.265	1.97
		section 2	5.5	0.373	4.88
15	KTB4-4	section 1	5.0	0.265	2.24
		section 2	5.5	0.373	2.97
16	KTB4-5	section 1	5.0	0.255	2.11
		section 2	5.5	0.363	2.79
17	KTB5-1	section 1	5.0	0.265	1.14
		section 2	5.5	0.382	1.64
18	KTB5-2	section 1	5.0	0.265	1.21
		section 2	5.5	0.382	1.64
19	KTB5-3	section 1	5.0	0.265	1.37
		section 2	5,5	0.382	1,60
20	KTB5-4	section 1	5.0	0.265	2.33
		section 2	5.5	0.382	2.90
21	KTB5-5	section 1	5.0	0.265	2.86
		section 2	5.5	0.382	2.11
22	KTB6-1	section 1	5.0	0.275	2.55
		section 2	5.5	0.382	3.80
23	KTB6-2	section 1	5.0	0.275	2.40
		section 2	5.5	0.382	3.80
24	KTB6-3	section 1	5.0	0.275	2.62
		section 2	5.5	0.382	2.91
25	KTB6-4	section 1	5.0	0.275	1.91
		section 2	5.5	0.382	4.45

6. CONCLUSIONS

The dam foundation of the Pac Ma Hydropower Project is developed in fractured porous rock with complex geological and hydrogeological conditions, which creates unfavorable conditions for seepage control. Based on the results of engineering geological investigations, an anti-seepage treatment using a grouting method with cement slurry and bentonite mortar incorporating sodium silicate additive was designed and implemented. The grouting system included six reinforcing rows and three curtain grouting rows, with a treatment depth of 10.5 m and vertically drilled boreholes arranged according to parameters determined from experimental grouting.

The experimental grouting stages indicated that grouting schemes with larger borehole spacing did not sufficiently reduce permeability. A denser borehole arrangement combined with the use of cement slurry and bentonite–sodium silicate mortar was therefore selected for the main construction stage. After completion of the grouting works, the quality of the anti-seepage treatment was evaluated by water pressure tests. Results obtained from 25 test boreholes showed Lugeon values ranging from 1.14 to 4.88, all of which are below the limit value of 5 specified in Vietnamese standards. The permeability reduction from 26–50 Lu to 1.14–4.88 Lu confirms the effectiveness of the staged multi-row grouting system under fracture-controlled conditions.

The test results indicate that the grouting works reduced the permeability of the treated dam foundation zone and formed a continuous grout curtain beneath the dam. Within the scope of this study, the applied grouting solution satisfies the technical requirements for seepage control at the Pac Ma Hydropower Project. The results provide practical data for the application of similar grouting schemes in dam foundations with comparable fractured porous rock conditions. By combining staged experimental adjustment, borehole spacing refinement, and comparative pre- and post-treatment Lugeon testing within a real construction environment, this study provides new field-based quantitative evidence that advances the understanding of fracture-targeted seepage mitigation mechanisms.

Foundation treatment using grouting methods contributes to improving the stability of the dam foundation while also altering the natural geological conditions of the area. Therefore, long-term documentation of geological conditions before and after treatment is necessary to support evaluation, comparison, and the refinement of the theoretical basis for foundation treatment. This documentation of the Pac Ma site also serves both as a technical record for dam safety and as a scientific and educational resource, contributing to geoheritage awareness and engineering geology training in Northwest Vietnam.

Although the short-term performance is satisfactory, the long-term durability of sodium silicate under continuous groundwater exposure requires further monitoring. Chemical interaction, potential leaching, and long-term strength evolution of the grout curtain were not evaluated in this study and should be investigated in future research.

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