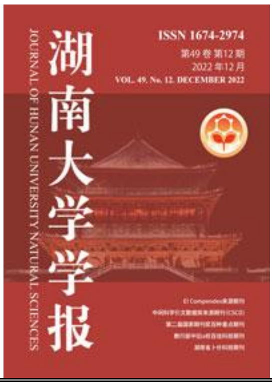

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Prediction of Grouting Method for Decreasing the Lugeon Value of Dam Foundation

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Abstract: This research aims to predict the grouting method to decrease the Lugeon value on the dam foundation. The methodology consisting of grouting is evaluated by comparing the first permeability (permeability before grouting) and secondary permeability (permeability after grouting). Grouting is critical in improving the dam foundation and reducing the permeability in Lugeon values. Because of the concealment and uncertainty of dam foundation grouting, the accurate evaluation of the quality of grouting construction has become a major concern. The effectiveness of the grouting method for decreasing Lugeon values in the dam foundation has not been certainly revealed. The foundation of the dam with weathered lapilli tuff and gravelly sand is a typical porous weathered rock. The grouting was performed as a down-stage, in which the grout hole is drilled in stages using a pneumatic packer. The improvement of the dam foundation by grouting is evaluated by comparing the first permeability (permeability before grouting) and secondary permeability (permeability after grouting) by using Lugeon values with a water pressure test. This test employed 534 data, which included the first permeability, depth, grout take, and secondary permeability. This paper focuses on modeling to predict the secondary permeability. The result is developing the secondary permeability that considers the relation between the parameters, which can affect and represent the characteristics of grouting quality in the non-linear regression equation that is SP = FP – f(GT) in the depth conditions of 5, 10, 15, 20, 25, and 30 m. R-squared is the coefficient of determination. The R-squared value for depths of 5, 10, 15, 20, 25, and 30 m is 87.52%, 83.18%, 72.29%, 60.20%, 42.25%, and 30.03%. Thus, the results are applicable to assess the quality of curtain grouting.

Keywords: dam foundation, grouting, permeability, quality assessment, the nonlinear regression methods.

降低壩基盧讓值的注漿方法預測

摘要：本研究旨在預測灌漿方法以降低壩基的盧讓值。通過比較一次滲透率（灌漿前的滲透率）和二次滲透率（灌漿後的滲透率）來評估由灌漿組成的方法。灌漿對於改善大壩基礎和降低盧讓值的滲透性至關重要。由於壩基灌漿的隱蔽性和不確定性，灌漿施工質量的準確評價成為人們關注的重點。用於降低壩基盧讓值的灌漿方法的有效性尚未明確揭示。風化火山岩凝灰岩和礫石壩基為典型的多孔風化岩。灌漿作為下階段進行，其中使用氣動封隔器分階段鑽灌漿孔。通過使用盧讓值和水壓試驗比較一次滲透率（灌漿前的滲透率）和二次滲

透率（灌漿後的滲透率），評估灌漿對壩基的改善。本次試驗採用了 534 個數據，包括一次滲透率、深度、注漿量和二次滲透率。本文側重於建模以預測次生滲透率。結果是開發了考慮參數之間關係的二次滲透率，它可以影響和表示非線性回歸方程中註漿質量的特徵，即 SP =计划生育– f(GT)在 5、10 的深度條件下 、15、20、25 和 30 米。R 平方是決定係數。5、10、15、20、25 和 30 米深度的 R 平方值為 87.52%、83.18%、72.29%、60.20%、42.25%和 30.03%。因此，該結果適用於帷幕灌漿質量的評估。

关键词：壩基、注漿、滲透率、質量評估、非線性回歸方法。

1. Introduction

Highly developed geological structures, such as faults, fractures, bedding planes, and shear zones, typically exist in the construction sites of these projects, which most likely constitute potentially concentrated leakage paths through the dam foundations and abutments during impounding and operation [1, 2].

Grouting is a method in which a mixture of the material penetrates the pore spaces, joints, cracks, and voids of rock, and soil structures. Therefore, grouting improves the physical and mechanical characteristics of these structures, the structures permeability of formations and deformability can be reduced. However, the strength of these formations will increase [1, 4-7].

Up to now, many studies have focused on examining the effects of curtain grouting to reduce the permeability of dam-foundation improvement [1, 4, 8]. The effectiveness of grouting depends on, permeability, grout composition method of injecting, and depth to grout. To determine rock permeability and groutability, the Lugeon test, the most common test, is employed. In this test, a packer and high pressure sealed the part of the borehole. Then, water is injected into it. Thus, permeability will be determined according to the rate of the water takes, pressure, and the length of the sealed borehole.

After the curtain grouting construction is completed, it is difficult to detect whether the quality of the grouting is good or bad. Moreover, it is a common problem to evaluate the grouting efficiency [2]. This study focuses on illustrating an efficient optimization design of grouting by comprehensively investigating data and simulations. However, in a dam foundation, it is possible to use data collected from completed grout sections to estimate the secondary permeability since the operation of grouting is usually performed in large quantities and over a long period of construction. It may be possible to record others properties of the grouting operation accurately, thereby, prediction methods are used to predict the secondary permeability [3].

Furthermore, different grouting curtain schemes are required at different locations of construction sites because of the different lithologies. Therefore, it is of great necessity to conduct an optimization design of the anti-seepage curtain for projects with a great dam height or relatively poor geological conditions during the seepage control design stage to save on construction costs and shorten the construction duration [2].

Curtain grouting is an important method for improving dam foundations. The quality of the curtain grouting is crucial to the safe operation of the dam. Therefore, it is necessary and crucial to evaluate the grouting efficiency [8]. A study that evaluates grouting efficiency can provide a direct basis for grouting engineers to take remedial measures because these measures significantly prevent leakage in the dam foundation and ensure the safe operation of the dam [7].

To improve grout, a dam foundation with a high Lugeon value requires more grout take. The trends of the permeability and the peak amount of grout take were basically consistent, indicating that the Lugeon test can reflect the amount of grout taken to a certain extent but cannot be used as an absolute reference for the amount of grout takes. Since different dam foundations rarely have the same geological properties, a predictive scheme may apply only to specific dam foundations.

This paper focuses on developing the secondary permeability by using the non-linear regression method of the grouting method foundation in the Bajulmati Dam weathered lapilli tuff and gravelly sand based on permeability, grout take, and conditions of rock mass discontinuities. The results are expected to be applicable to assess the quality of curtain grouting. This test employed 534 data, which included the first permeability, depth, grout take, and secondary permeability

2. Objectives

The Bajulmati Dam is located in Watukebo Village, Wongsorejo District, Banyuwangi Regency, East Java Province, Indonesia. Bajulmati dam is a central core of the rock-fill dam with a 56.8 m height from the foundation, crest length and width of 250 m and 6 m wide. The general layout of the Bajulmati dam site is presented in Fig. 1.

The dam is built to control water flood, a water supply of 110 l/s, and an irrigation water area of 1800 ha. The foundation of the dam is located in two young volcanic deposits, namely, the Ijen Tua volcanic deposit consisting of lapilli tuff and gravelly sand and the Baluran volcanic deposit consisting of lava flow and auto breccia. The geological of the dam site is presented in Fig. 2.

The Lugeon value on the dam foundation before grouting is almost entirely more than a value of 5 to a foundation depth of 30 m. The improvement of the dam foundation by grouting is evaluated by comparing the first permeability (permeability before grouting) and secondary permeability (permeability after grouting). Therefore, it is necessary to evaluate and assess the grouting efficiency of dam foundation based on Lugeon values.

3. Methods

3.1. Grouting Operations

Grouting is systematic borehole drilling conducted beneath and beside the structures to decrease the permeability and improve the rock quality [1, 4-7].

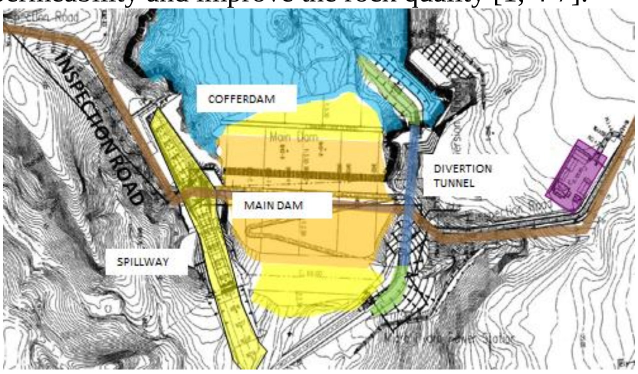

Fig. 1 General layout of Bajulmati dam site

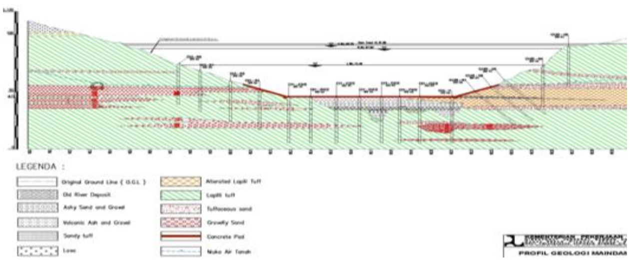

Fig. 2 Geological conditions of the Bajulmati dam

The grouting has been performed at a down-stage. The grout hole has six grout stages (5, 10, 15, 20, 25, and 30 m).

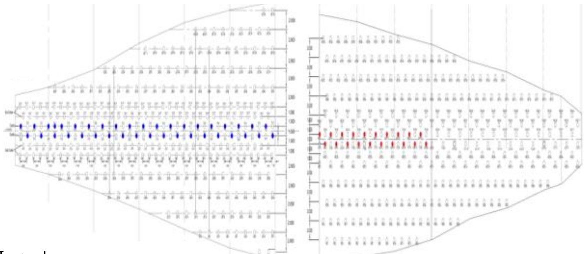

Fig. 3. Layout of grouting holes in Bajulmati dam foundation

The process of grouting in each grout section was arranged into four sequences: drilling, washing, water testing, and grouting. During water testing, the Lugeon tests were required to obtain Lugeon values, which provide the permeability of a specific grout section. Each grout section contains data on depth, grout take, Lugeon values of the first permeability, and Lugeon values secondary permeability.

3.2. Permeability Test

Water Pressure Test (WPT) is the most common method to test the permeability and grout ability of rock masses. M. Lugeon first conducted this experiment in 1933 and Lugeon values (LU) expressed the permeability rate. One Lugeon unit = is 1 Liter of water/meter of test hole/minute at an injection pressure of 10 bar (approximately 150 psi). The result of this test shows the degree of permeability in the dam foundation [1, 3, 7, and 10].

This test employed 534 data on the first permeability, depth, grout, take and secondary permeability. The samples of dataset are presented in Table 1.

Table 1 Samples of dataset (Own study)

Depth (m)	**First permeability (Lu)**	**Grout takes (kg/m)**	**Secondary permeability (Lu)**
5	26.19	794.2	6.61
5	17.07	89.19	3.07
10	25.61	987.45	7.24
15	7.69	57.26	7.63
20	15.84	50.59	11.43
20	15.39	60.87	11.28
25	8.50	809.80	1.56
25	13.12	479.00	6.18
30	7.75	394.00	1.14
30	5.71	595.70	3.88

The first permeability refers to the permeability before grouting, and the secondary permeability refers to the permeability after grouting.

Grout take refers to the volume of injected grout. May refers to the total injected volume in an interval within a hole, in an entire grout hole, in a unit length or area of a grout curtain, or the entire rock formation or soil mass. The grouting material was a mixture of cement and bentonite. The volume of bentonite was 5% of the cement volume.

3.3. Data Analysis

The depths of each grout section were 5, 10, 15, 20, 25, and 30 meters. Each section contained data on the length of grout sections, lugeon values, and grout take. The data were analyzed by combining the data of the first permeability, the secondary permeability, and grout takes. All data were collected from the inspection chart of the curtain grouting for the Bajulmati dam foundation in 2009.

The parameter of independent variable research such as the first permeability and grout take, however, the dependent variable is the secondary permeability.

To facilitate the analysis process, this study has adopted the Lu symbol to represent Lugeon values. Meanwhile, the grout take of a grout section was divided by its length to obtain the unit grout take per unit length (kg/m).

Then, all data were calculated and analyzed using the SPSS program. Then there is carried out by building the prediction model of secondary permeability in each depth of 5, 10, 15, 20, 25, and 30 m. Fig. 4 presents a flow chart of the study.

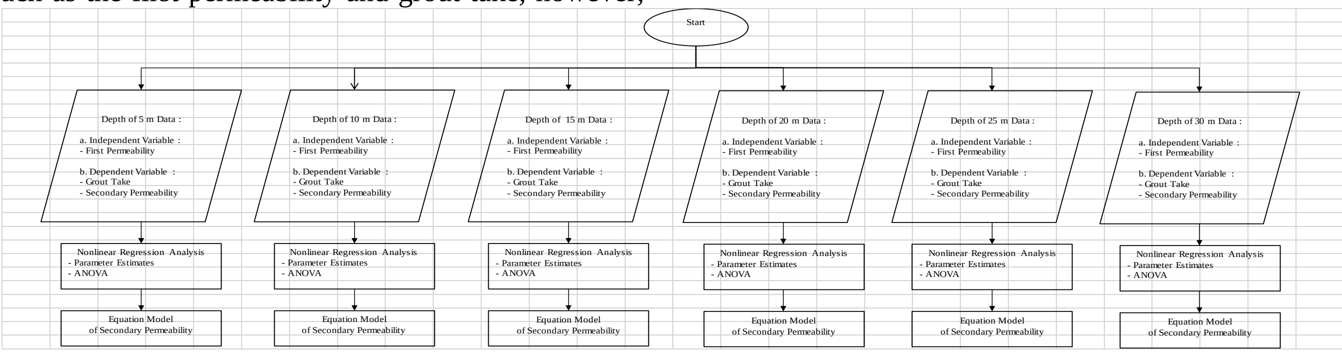

Fig. 4 Flowchart of the study (Own study)

Table 2 Condition of rock mass discontinuities with different Lugeon values (after [11]) (Own study)

Range of Lugeon	Classification	Range of hydraulic conductivities (cm/s)	Conditions of rock mass discontinuities	Precise report (Lugeons)
< 1	Very low	$< 1 \times 10^{-5}$	Very tight	< 1
1 – 5	Low	1×10^{-5} - 6×10^{-5}	Tight	± 0
5 – 15	Moderate	6×10^{-5} - 2×10^{-4}	Few partly open	± 1
15 – 50	Medium	2×10^{-4} - 6×10^{-4}	Some open	± 5
50 – 100	High	6×10^{-4} - 1×10^{-3}	Many open	+ 10
> 100	Very high	$> 1 \times 10^{-3}$	Open and closely spaced or void	> 100

4. Result and Discussion

4.1. Results of Grout Hole

This study has revealed corresponding relationships between the secondary permeability and the first permeability, depth of grouting, and grout take. The test positions were selected at depths of 5, 10, 15, 20, 25, and 30 m.

4.1.1. Depth of 5 m

The first permeability (permeability before grouting) ranged from 5.35 – 50.44 Lu. The first permeability of the permeability class shows a moderate to high permeability value, and the conditions of rock mass discontinuities are partly open to many open.

In the 5 m depth, there is obtained the non-linear regression equation model as follow: SP = FP – 0.032 GT that is significant by the level of 95% (-0.039 until -0.026). In this research there is obtained the influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) is about 87.52%.

4.1.2. Depth of 10 m

The first permeability ranges from 5.68–53.69 Lu. The first permeability of the permeability class shows a moderate to high permeability value, and the conditions of rock mass discontinuities are partly open to many open.

For the 10 m depth is obtained the non-linear regression equation model as follow: SP = FP – 0.022 GT that is significant to the level of 95% (-0.026 until -0.018). The influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) in the 10 m depth is about 83.18%.

4.1.3. Depth of 15 m

The values of the first permeability range from 4.90–78.51 Lu. The first permeability of the permeability class shows low to high permeability values, and the condition of rock mass discontinuities is few partly open to many open.

For the 15 m depth is obtained the non-linear regression equation model as follow: SP = FP – 0.013 GT that is significant to the level of 95% (-0.018 until -0.009). The influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) in the 15 m depth is about 72.29%.

4.1.4. Depth of 20 m

The value of the first permeability ranges from 5.05–44.67 Lu. The first permeability value the permeability class shows moderate-to-medium permeability values, and conditions of rock mass discontinuities are few partly open to some open.

For the 20 m depth is obtained the non-linear regression equation model as follow: SP = FP – 0.009 GT that is significant to the level of 95% (-0.011 until -0.007). The influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) in the 20 m depth is about 60.20%.

4.1.5. Depth of 25 m

The values of the first permeability range from 5.05–18.06 Lu. The first permeability of the permeability class shows moderate-to-medium permeability values, and conditions of rock mass discontinuities are few partly open to some open.

For the 25 m depth is obtained the non-linear regression equation model as follow: SP = FP – 0.008 GT that is significant to the level of 95% (-0.012 until -0.005). The influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) in the 25 m depth is about 42.25%.

4.1.6. Depth of 30 m

The values of the first permeability range from 5.23–35.07 Lu. The first permeability of the permeability class shows moderate-to-medium permeability values, and conditions of rock mass discontinuities are few partly open to some open.

For the 30 m depth is obtained the non-linear regression equation model as follow: SP = FP – 0.007 GT that is significant to the level of 95% (-0.010 until -0.004). The influenced percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP) in the 30 m depth is about 30.03%.

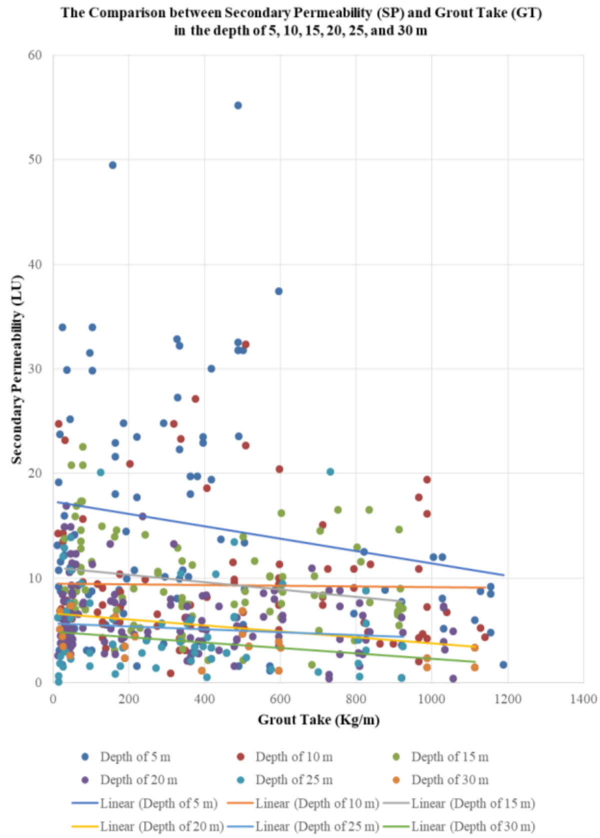

Fig. 4 The comparison between secondary permeability (SP) and grout take (GT) at depths of 5, 10, 15, 20, 25, and 30 m (Own study)

4.2. Discussion of the Relationship between Grout Take and Permeability after Grouting (Secondary Permeability)

After observing the permeability and grout take, the data were analyzed by combining the first permeability (permeability before grouting), grout takes, and permeability after grouting.

This research only obtains Lugeon values as the only physical parameter to evaluate the effect of grout take. This value shows the degree of permeability of the dam foundation. In grout improvement, a dam foundation with a high Lugeon value requires more grout take.

Fig. 4 shows the data distribution of grout take (GT) to the secondary permeability (SP) in the depth of 5, 10, 15, 20, 25, and 30 m. The equation shows the prediction of data distribution toward the decreasing line diagram. The bigger grout takes causes the smaller value of secondary permeability. This result is matched with the non-linear regression equation model as follow: SP = FP -f (GT), which shows that the coefficient of GT is negative. The negative coefficient explains that there is an influence of GT on the vice versa effect from GT to SP.

R-squared (R^2) is mentioned as the coefficient of determination. The value of R-squared that is in the range of 0 until 1 is an important value because R-Squared indicates how far feasible the model is used.

Based on the analysis in Table 3, in this research, the deeper grouting depth is done, so there is a smaller influence of grout take (GT) on the secondary permeability (SP). However, the deeper grouting depth is done, so there is a smaller influence percentage of first permeability (FP) with the grout take (GT) to the secondary permeability (SP).

The hydrogeological structure of the dam foundation consists of a fracture network structure and a vein structure. The permeability of the dam sites is not uniform. Weathered lapilli tuff dominates the geological type in depths of 5–15 m. Meanwhile, gravelly sand dominates the geological type in depths of 20–30 m.

Table 3 Equation model of secondary permeability at each depth (Own study)

Depth (m)	**Equation Model**	**Level of 95%**		**Note**	**R^2 (%)**
		Lower limit	**Upper limit**		
5	SP = FP – 0.032 GT	-0.039	-0.026	Significant	87.52
10	SP = FP – 0.022 GT	-0.026	-0.018	Significant	83.18
15	SP = FP – 0.013 GT	-0.018	-0.009	Significant	72.29
20	SP = FP – 0.009 GT	-0.011	-0.007	Significant	60.20
25	SP = FP – 0.008 GT	-0.012	-0.005	Significant	42.25
30	SP = FP – 0.007 GT	-0.010	-0.004	Significant	30.03

The process of grouting in each grout section was arranged into four sequences: drilling, washing, water testing, and grouting. During water testing, the Lugeon tests were required to obtain Lugeon values, which provide the permeability of a specific grout section. Each grout section contains data on depth, grout take, Lugeon values of the first permeability, and Lugeon values secondary permeability.

This modeling is to predict the secondary permeability by using the grouting method in the Bajulmati dam foundation.

Based on the Lugeon values of the first and secondary permeability and grout take data, this study concludes several points:

1. The permeability class for the Bajulmati dam foundation in depths of 5–30 m based on first permeability is moderate to medium permeability (5–50 Lu), and conditions of rock mass discontinuities is few partly open to some open.

2. This research obtains the non-linear regression equation model for each depth. Based on the determination result (R^2), the deeper grouting depth is done, so there is a smaller influence percentage of the first permeability (FP) with the grout take (GT) on the secondary permeability (SP). The depths of 5, 10, 15, 20, 25, and 30 m each have the following determination values (R^2) as follow: 87.52%, 83.18%, 72.29%, 60.20%, 42.25%, and 30.03%.

3. For the next research, the type of geology is entered into the prediction model of secondary permeability.

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