Journal of Geomine (2025), 3(2), 82-92
DOI: 10.22077/jgm.2025.9533.1051

Statistical analysis and validation of cement slurry flow rate calculated by analytical and numerical models in grouting process

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Recived: 2025 Jun. 03, Revised: 2025 Aug. 12, Online Published: 2025 Aug. 18

ABSTRACT

Grouting operations are widely used to reduce leakage and increase the strength and consolidation of jointed rock in construction sites. One key challenge in these operations is accurately estimating the volume of cement slurry required. Precise estimation enables the grouting process to be optimized both technically and economically, and it also allows for predicting grout penetration in sections with similar conditions based on the results. This research focuses on estimating the cement slurry volume using both analytical and numerical models. Five analytical models are introduced, each assuming the presence of a joint with a constant aperture bb, and calculating the penetration volume accordingly. For numerical modeling, UDEC software was employed. In this approach, the cross-section of the block, the borehole, and the grouting joint were modeled, followed by the application of grout properties and the ultimate grouting pressure. Geotechnical and grouting data from the Seymareh Dam site were used as a case study. To validate the models, statistical analyses were conducted under varying conditions of rock quality factor and grouting section depth. Based on the overall results, analytical model number 4 demonstrated the best accuracy in estimating grout volume, while model number 5 showed the weakest performance. Therefore, if a single model is to be selected, model number 4 is recommended.

KEYWORDS

Grouting, grout volume, analytical and numerical models, correlation coefficient, cross-section depth

I. INTRODUCTION

One of the most critical challenges during both the study phase and the construction stage of dam projects is waterproofing the foundations of these water structures. Foundation permeability has consistently posed a significant problem for dam builders. Controlling water leakage and reducing the hydraulic gradient are crucial factors, especially during the initial stages of water intake operations. To address these issues, various solutions have been proposed, with the most effective being the construction of a waterproofing curtain using the cement grout grouting process (Li et al., 2016a).

Grouting cement grout into jointed rocks is a challenging process due to the complex and often unknown nature of the ground. Accurate prediction and calculation of key grout volume parameters, such as the amount required for grouting and the penetration radius, are challenging to achieve.

To better understand these parameters, it is necessary to simplify the geometric characteristics of the rock and the grout penetration conditions (Li et al., 2016a). In this approach, rock joints which serve as the pathways for grouting flow are represented by circular disks with apertures equal to the average joint aperture. These disks are classified based on their permeability: those that allow only water to pass are called water channels, while those with larger apertures that permit grout flow are referred to as grouting disks (Li et al., 2016b). The grouting borehole is assumed to be located at the center of the disk, with the disk's radius corresponding to the effective radius of the grouting operation (Yanjie and Chengchao, 2013).

The cement grout used in grouting operations behaves as a Bingham fluid. Therefore, its rheological properties including viscosity (μ) and yield stress (τ_0) govern its flow behavior. The viscosity, flow velocity, and yield stress primarily determine the maximum penetration length of the grout within the borehole, given specified grouting pressures and a constant joint aperture (Ewert, 2000). The maximum effective radius of the grouting operation is directly proportional to the final grouting pressure and the joint aperture, and inversely

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proportional to the grout's yield stress and viscosity (Bambang and Andre Primantyo, 2023).

In grouting modeling, in addition to grout properties, the geometric conditions of the engineering site such as the aperture of joints are critically important. Generally, joint aperture is one of the most sensitive parameters when evaluating the penetration radius of cement grout. By analyzing test results, pressure data, drill core samples, and recorded grout take volumes, an approximate estimation of the joint aperture can be obtained (Xia et al., 2018). Moreover, operational factors, particularly the applied grouting pressure, also significantly influence the penetration of cement grout (Zhang et al., 2014).

The purpose of this study is to investigate the grouting operation in order to estimate the required grout volume. Accurate estimation of these parameters is essential for effective grouting, as it enhances designers' ability to determine the appropriate grouting pressure to avoid fracturing or damaging the rock mass, estimate grout penetration length and volume, and generally optimize the grouting process from both technical and economic perspectives (Widmann, 1996). This study introduces various analytical models proposed by researchers for estimating grout volume and also employs numerical modeling using UDEC software to examine their application principles. The grouting results from the Seymareh Dam construction site were used as a case study to analyze these models. Recognizing the critical importance of precise grout volume estimation, the results from the analytical and numerical models were compared with actual grout take data from the site's boreholes (Zhang et al., 2018). This comparison was performed using Kraft's statistical methods, followed by an investigation into the effects of two parameters Rock Quality Designation (*RQD*) and section depth on the grouting process (Houlsby, 1990).

II. GROUTING MODELING

A. *Analytical Grouting Modeling*

Using analytical models, the volume of cement slurry can be estimated by simulating the grouting process within the rock mass. These models take continuous data from grouting operations, along with the slurry's rheological properties, as inputs and ultimately provide a reliable estimate of the required grout volume. Table 1 presents the most significant analytical models for cement slurry volume estimation, as proposed by various researchers (Shroff and Shal, 1999).

Model 1 is based on the assumption that the rock mass contains a single joint. This joint is represented as a disk with a constant aperture, b. When grouting begins, the grout uniformly affects the entire disk radially outward from the borehole, which is located at the center of the disk. The radius of the disk influenced by the grout is called the effective radius, I. It should be noted that the number of groutable disks along the borehole corresponds to the number of water channel disks (Cheng et al., 2019).

Model 2 assumes that grout will be injected into a set of joints and current channels in the rock, with an expansion angle denoted by α. The permeable parts of the rock are modeled as circular and disk-shaped joints, with the grouting borehole located at the center of the disk. The ideal expansion angle of grout inside the joint is $\alpha = 2\pi$; however, if only a small portion of the joint is permeable, the angle is smaller.

The expansion angle of grout in this sector, defined by α, is determined empirically based on the mechanical properties of the rock, as shown in Table 1. This table presents the values of the expansion angle (α) corresponding to the RMR index (Dalmalm, 2004).

Model 3 is based on a principle similar to that of Model 2. However, in this model, the perimeter of the borehole circumference (W) also plays a significant role in evaluating grout take. The area of grout penetration into the rock mass and the volume of grouting in boreholes of different radii and thus different perimeters will vary (Hakansson et al., 1993).

Model 4 calculates the grout volume per square meter of bearing area using the following equation, where L represents the length of the grouting sector (Liu et al., 2018).

Model 5 describes grout flow from the borehole into a set of circular disks. Each disk has an average aperture, $\bar{b}$, and a grout penetration radius, I. The main disk, which intersects the borehole, also contacts secondary disks. Changes in aperture are defined by the geometric parameters θ, β, and K. These parameters account for differences between grout and water penetration in the rock, the curved flow of grout, and the effects of secondary disks. The average joint aperture, $\bar{b}$, can be obtained by multiplying the parameter θ by the average hydraulic aperture (b), which is determined by the Lugeon test (Zheng et al., 2019).

The coefficient β represents the ratio of the total joint area to the area of the initial disk. The number of groutable disks, Ng, that intersect the bearing surface is obtained by multiplying the conversion parameter k_j by Nw, the number of water channel disks:

$$N_w \,.\, N_g = K_w \tag{1}$$

Penetration radius, I, is defined by aim of b_g and K_1 where k_3 is the parameter of curve path of joints in the disk. Parameter k, is the ratio of grouting able joint aperture, b_g , to the hydraulic aperture of the joint:

$$K = b_g / b \tag{2}$$

In the relationships in Table 1, I is the radius of penetration of the grout, b is the joint opening, τ_0 is the yield stress (adhesion) of the grout, Δp is the difference between the grouting pressure and the groundwater pressure, α is the angle of expansion of the grout, W is the circumference of the grouting borehole, L is the length of the grouting section, N_g is the number of injectable discs, b_g is the opening of the injectable joint, K_3 is the curved path parameter of disc (Janson et al., 1993).

Table 1. Analytical models for estimating the volume of cement slurry

Model number	Description	The relationship presented
1	$I = \Delta P.b / (2\tau_0)$	$V = I^2.b.\pi$
2		$V = I^2.b.\alpha / 2$
3		$V = (\Delta P/2\tau_0).b^2.[W+((\Delta P.b/2\tau_0).\alpha/2)]$
4		$V = I^2.b.L/2$
5	$I = \Delta P.b_g / (2\tau_0.K_3)$ $\bar{b} = \theta.b$	$V = I^2.\bar{b}\pi.\beta.N_g$

B. Numerical modeling of grouting

In this method, numerical modeling was performed using UDEC software. In this software, the rock mass is represented as a set of discrete blocks separated by discontinuity surfaces (joints). The blocks themselves are considered impermeable, and fluid flow is restricted to the joints. Based on the input data, the software applies the final grouting pressure to the joint openings, calculates the grout penetration rate, and presents the results in graphical plots. The numerical modeling is based on steady-state flow analysis, with grout penetration endpoint conditions where the system reaches a steady state. Fig. 1 illustrates grout penetration from the grouting borehole into the rock mass as simulated by UDEC software.

The following parameters were initialized as input parameters:

- Rock mass geometry;
- Grouting section located at the center of the rock mass;
- Horizontal grouting joint positioned at the center of the borehole;
- Average joint opening estimated from core sampling data and Lugeon test results at the Seymareh site;
- Density and yield stress of the cement slurry, calculated from Marsh funnel test results;
- Final grouting pressure estimated based on pressure values recorded at the Seymareh grouting workshop;

Table 2 summarizes the input parameters used for the numerical modeling.

Table 2. Input parameters for numerical modeling

Row	Parameter value	Input parameter name
1	5×20 m	Dimensions of the grouting rock mass
2	5 m	Grouting section
3	0.5-1 mm	Joint opening (b)
4	1130 kg/m^3	Grout density
5	21 Kg/ms^2	Grout yield stress
6	10-40 atm	Grouting pressure
7	1:1, 2:1	Water to cement ratio

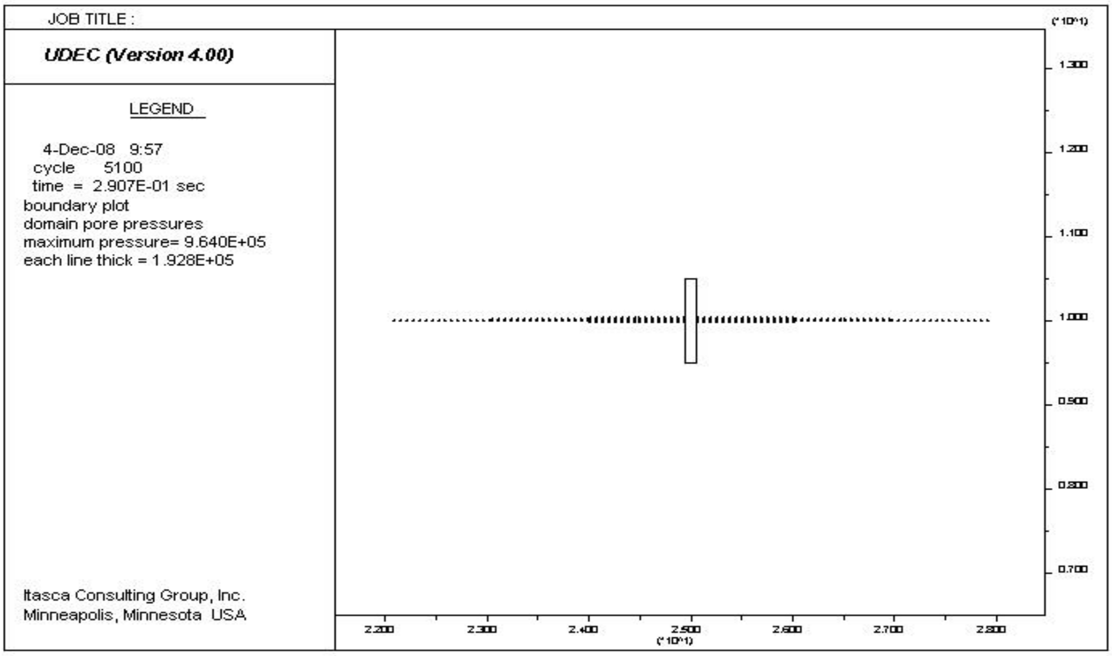

Fig. 1. Demonstration of slurry penetration from the grouting borehole into the rock mass using UDEC software

III. Study Area

The Seimareh Dam and Power Plant construction site is located on the Seimareh River, approximately 40 km northwest of Darehshahr County in Ilam Province, and about 7.5 km from Cheshme Shirin Village. The project aims to harness the hydroelectric potential of the Seimareh River. The dam is designed as a thin double-arch concrete structure, standing 130 meters above the current riverbed (approximately 180 meters above the bedrock). The dam crest elevation is 730 meters, with the normal water level at 720 meters above sea level. The dam crest length at this elevation is 202 meters. The reservoir capacity is approximately 215.3 billion cubic meters.

IV. Calculation of the Volume of Grouting Slurry

Based on the analytical and numerical models introduced earlier and using data from the Seimareh Dam site, the volume of injected grout slurry was calculated. Table 3 presents example results of slurry volume estimations using analytical models 1 through 5 (denoted as V1 to V5) and numerical modeling (VUDEC for real flow, denoted as Vreal) for two boreholes.

V. Statistical Analysis of Modeling Results

Given the technical and economic importance of accurately estimating cement grout volume, the results of both analytical and numerical modeling were compared with actual grout volumes recorded from the grouting boreholes at the Seimareh Dam site. This validation was performed using statistical methods. Subsequently, the influence of two parameters Rock Quality Designation (RQD) and section depth on the grouting process was investigated. The statistical methods applied are described below:

A. *Comparison of analytical and numerical modeling results based on statistical methods*

In this section, using the previously introduced statistical methods, the results of the analytical and numerical models are compared with the actual grout volumes. First, scatter plots comparing the modeled data to the real grout volumes for each section were created. Then, the correlation coefficient and the mean squared error (MSE) between the modeled grout volumes and the actual volumes were calculated. Fig. 2 shows the scatter plots comparing the computed and actual grout volumes.

Table 4 presents the correlation coefficients and mean squared errors calculated between the results of each modeling approach and the real grout volumes. As shown, based on the correlation coefficient, models 1 to 4 outperform the numerical modeling, with model 5 being the least accurate. According to the mean squared error, model 4 demonstrates the highest accuracy, followed by models 1 to 3, which also perform better than the numerical model. Again, model 5 provides the poorest estimates of grout volume.

B. *Statistical analysis of results based on rock quality coefficient (RQD)*

In this section, considering the significance of the Rock Quality Designation (RQD) on grout flow, the results have been categorized based on RQD values at different grouting sections. According to the available data, 90 percent of the rock sections fall within the medium to high-quality range. Consequently, the rock mass was divided into three general categories, which are analyzed below:

Table 3. Calculated slurry flow in cubic meters using analytical and numerical models, a- in borehole c-19 and b- in borehole p-23

(A)

Depth (m)	RQD	Lu	V_{real} (m^3)	V1	V2	V3	V4	V5	V_{UDEC}
0-5	60.6	1	0.01891	0.0015	0.0001	0.0002	0.00049	0.00015	0.00048
5-10	81.6	14	0.11045	0.0067	0.0008	0.0009	0.00216	0.00978	0.00184
10-15	75.8	4.3	0.01575	0.0139	0.0017	0.0019	0.00445	0.00597	0.00406
15-20	95.4	1.3	0.01891	0.0276	0.0105	0.0108	0.0088	0.00356	0.00704
20-25	82.2	7.4	0.05175	0.0338	0.0043	0.0045	0.01079	0.02491	0.00711
25-30	90.2	4.3	0.01321	0.0464	0.0177	0.0180	0.01477	0.01982	0.00998
30-35	92	1	0.01575	0.0609	0.0233	0.0236	0.01941	0.00605	0.01457
35-40	59.4	1	0.01704	0.0891	0.0113	0.0118	0.02838	0.00885	0.02301
40-45	85	1	0.01704	0.1233	0.0157	0.0162	0.03927	0.01225	0.04428

(B)

Depth (m)	RQD	Lu	V(m^3)	V1	V2	V3	V4	V5	V_{UDEC}
0-5	44.8	51	0.17262	0.0015	0.0000	0.000	0.00048	0.00773	000.0081
5-10	54	72	0.12333	0.0035	0.0002	0.000	0.00112	0.02530	0.00103
10-15	83.4	10	0.02666	0.0081	0.0010	0.001	0.00260	0.00836	0.00281
15-20	84.6	5	0.01945	0.0176	0.0022	0.002	0.00561	0.00876	0.00542
20-25	91	4.1	0.04941	0.0189	0.0072	0.007	0.00603	0.00772	0.00544
25-30	87.6	95	3.11083	0.0322	0.0041	0.004	0.01026	0.30437	0.00900
30-35	72.4	6.1	0.07466	0.0436	0.0055	0.005	0.01391	0.02647	0.01001
35-40	92.4	1.8	0.12766	0.0626	0.0239	0.024	0.01993	0.01132	0.01858
40-45	94	1	0.00483	0.0829	0.0316	0.032	0.02640	0.00823	0.02320
45-50	87	1.5	0.02108	0.1289	0.0164	0.016	0.04107	0.04869	0.04410
50-53	44.8	3.2	3.98665	0.1493	0.0095	0.010	0.04757	0.27013	0.04824

1) The quality of the rock is in the medium range

Sections with an RQD between 50 and 75 fall into this category. Table 5 presents the calculated correlation coefficients between the grout volumes predicted by the analytical and numerical models and the actual grout volumes. In this category, there is a strong positive correlation between the predicted and actual grout volumes. According to the table, the first through fourth analytical models produce similar results and outperform the other models. Numerical modeling ranks next, with only a slight difference in accuracy. The fifth analytical model shows the weakest performance among all the models.

Table 5 also presents the mean squared errors (MSE) between the analytical and numerical grout volume estimates and the actual grout volumes for sections with average rock quality. According to these results, based on the MSE comparison, the fourth analytical model performs best, followed by the numerical model and the fifth analytical model. The first analytical model exhibits the highest error among all models.

2) The rock quality is in the good range

This category includes sections with RQD values between 75 and 90. Table 6 shows the correlation coefficients between the analytical and numerical grout volume estimates and the actual grout volumes for sections with good rock quality.

In this category, there is no significant correlation between any of the models and the actual grout volumes, indicating that none of the models successfully predict grout behavior in sections with good rock quality. Table 6 also presents the mean squared errors (MSE) between the analytical and numerical grout volume estimates and the actual volumes for these sections. According to the MSE values, the second and third analytical models exhibit the lowest errors, while the first and fifth analytical models show the poorest performance.

3) Rock quality is in the excellent range

Sections with RQD values between 90 and 100 fall into this category. Table 7 shows the correlation coefficients between the analytical and numerical model estimates and the actual grout volumes. In this category, a relatively weak correlation of about 0.396 exists between the results of the first to fourth analytical models and the actual grout volumes. Numerical modeling follows closely with a correlation coefficient of 0.391. Again, the fifth model shows the weakest performance among all models.

A comparison of geomechanical rock classifications based on correlation coefficients indicates that sections with excellent rock quality yield weaker model predictions compared to sections with average rock quality.

Table 7 also shows the mean square of the differences between the analytical and numerical corrosion parameters and the actual corrosion value in sections with good rock quality. According to the mean square method, the fourth analytical model and the numerical model have the lowest error among the other models. Also, the first and fifth analytical models provide the weakest results. Fig. 3 shows the results obtained from the comparison between the models based on the mean square method of differences in each of the rock divisions. According to this figure, it can be said that in all modeling, except for the fifth model, the second group of sections with RQD between 75 and 90 shows the lowest error in modeling.

Table 4. Comparison of computational fit from analytical and numerical models with actual fit, using: A- Correlation coefficient and B- Mean square of differences

(A)

Parameters		Correlation coefficient
Vreal	V1	0.50365
Vreal	V2	0.50735
Vreal	V3	0.50746
Vreal	V4	0.50365
Vreal	V5	0 32197
Vreal	V udec	0.49204

(B)

Parameters		Mean square of differences
Vreal	V1	0.001525
Vreal	V2	0.001582
Vreal	V3	0.001591
Vreal	V4	0.001276
Vreal	V5	0.002496
Vreal	V udec	0.00146

Table 5. Comparison between the calculated volume from analytical and numerical models with the actual corrosion in sections with average rock quality, using: A- Correlation coefficient and B- Mean square of differences

(A)

Parameters		Correlation coefficient
Vr	V1	0.71597942
Vr	V2	0.716937
Vr	V3	0.7163821
Vr	V4	0.715976
Vr	V5	0.5276903
Vr	V udec	0.69729761

(B)

Parameters		Mean square of differences
Vr	V1	0.007779
Vr	V2	0.000774
Vr	V3	0.000759
Vr	V4	0.000511
Vr	V5	0.000634
Vr	V udec	.000621

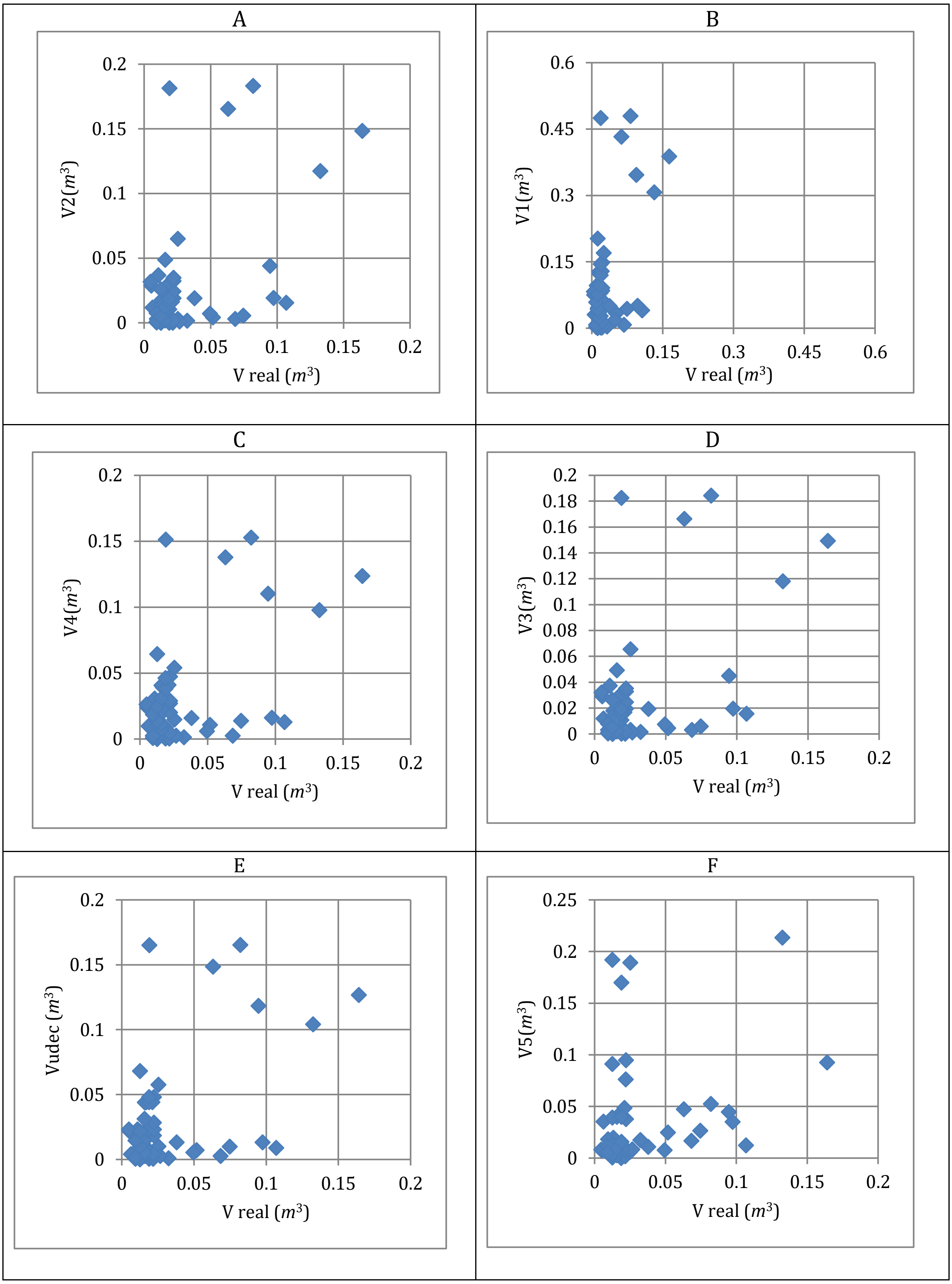

Fig. 2. Scatter plot of calculated pore volume from analytical models 1 to 5 with actual pore volume

Table 6. Comparison between calculated corrosion from analytical and numerical models with actual corrosion in sections with good rock quality, using: A- Correlation coefficient and B- Mean square of differences

(A)

Parameters		Correlation coefficient
Vr	V1	-0.07475
Vr	V2	-0.07476
Vr	V3	-0.07365
Vr	V4	-0.07476
Vr	V5	0.015284
Vr	V udec	-0.08812

(B)

Parameters		Mean square of differences
Vr	V1	0.005654
Vr	V2	0.000286
Vr	V3	0.00028
Vr	V4	0.000507
Vr	V5	0.002657
Vr	V udec	0.000584

Also, sections with excellent rock quality have the highest error among other sections in terms of modeling. The fifth model is the only exception in this section, as the modeling error increases with increasing rock quality. Fig. 4 shows the results obtained from comparing models based on the mean square method of differences in sections with different rock quality.

C. Statistical Analysis of Results Based on the Depth of the Grouting Section

One of the key factors influencing the amount of cement grout absorbed by rock masses is the depth of the grouting section. Rocks with similar characteristics can accommodate varying amounts of grout at different depths. Generally, it is expected that with increasing depth—due to higher overburden pressure on the underlying layers and a reduction in the size and number of joints—the volume of grout intake will decrease. However, it is important to note that the quality of the rock plays a significant role, and this expected trend does not always hold.

In this section, the depth of the grouting section is analyzed separately to investigate its effect on grout volumevariations more accurately and to compare predictive models. The grouting borehole sections are categorized into four groups based on depth. For each group, the correlation coefficient and the mean squared error (MSE) between the actual and predicted grout volumes are analyzed.

The classification is as follows:

- Depths of 0 to 15 meters are considered surface sections
- Depths of 15 to 30 meters are medium-depth sections
- Depths of 30 to 45 meters are deep sections
- Depths greater than 45 meters are categorized as very deep sections.

1) Surface sections

The correlation coefficients and the mean squared differences between the results of the studied models and the actual grout volumes are presented in Table 8.

The results presented in Table 8 indicate that, in the surface sections, only the second and third models show a correlation with the actual grout intake. In contrast, the remaining models exhibit no significant correlation. According to the mean squared difference method, the first analytical model demonstrates the lowest error, whereas the second and third models show the highest error among all the models analyzed.

2) Medium sections

The correlation coefficients and mean squared differences for the parameters in this group are presented in Table 9. In these sections, none of the models show a correlation with the actual grout intake, indicating the absence of a linear relationship between the model predictions and the actual data. This suggests that none of the models were successful in accurately capturing the behavior of grout intake at medium depths. However, based on the mean squared differences, the first analytical model exhibits the lowest error among all models. In contrast, the fifth analytical model and the numerical model perform the weakest in this group.

Table 7. Comparison between calculated corrosion from analytical and numerical models with actual corrosion in sections with very good rock quality, using: A- Correlation coefficient and B- Mean square of differences

(A)

Parameters		Correlation coefficient
Vr	V1	0.396074
Vr	V2	0.396073
Vr	V3	0.396023
Vr	V4	0.396073
Vr	V5	0.299956
Vr	V udec	0.391329

(B)

Parameters		Mean square of differences
Vr	V1	0.02394
Vr	V2	0.003051
Vr	V3	0.003075
Vr	V4	0.002452
Vr	V5	0.003658
Vr	V udec	0.002757

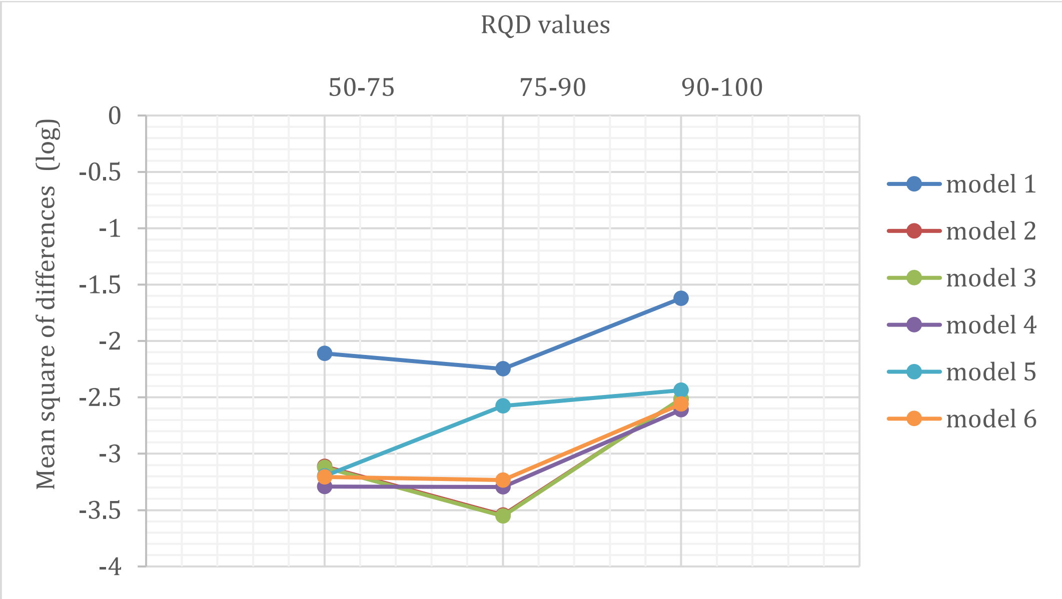

Fig. 3. Results obtained from the logarithm of the mean square of differences comparison between models based on the mean square differences method based on RQD values.

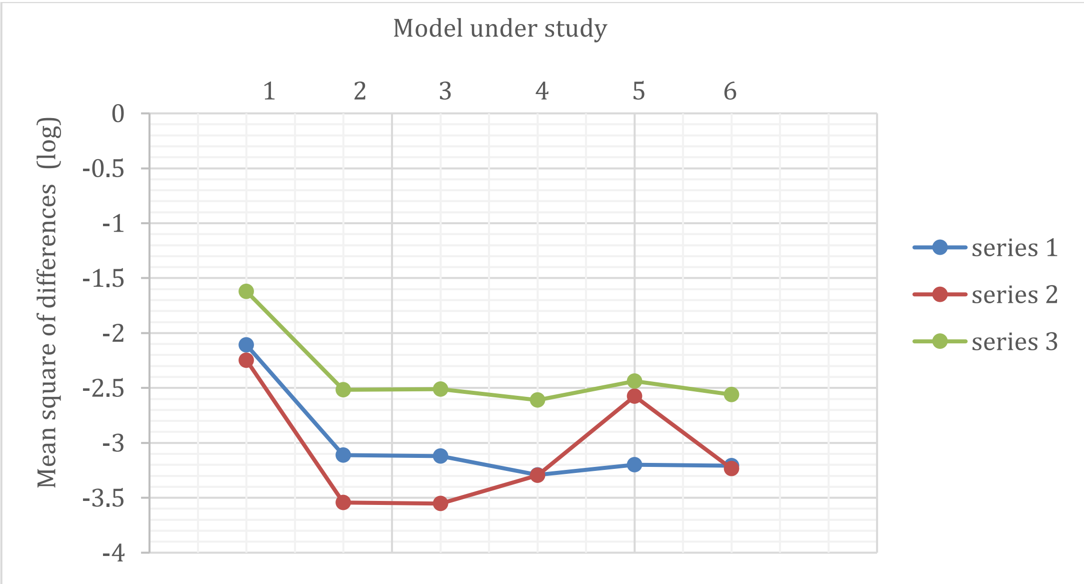

Fig. 4. Results obtained from the comparison of models based on the logarithm of the mean square of differences in sections with different rock quality

Table 8. Comparison of calculated vorticity from analytical and numerical models with actual vorticity in surface sections using, A-correlation coefficient and B- mean square of differences

(A)

parameters		Correlation coefficient
Vreal	V1	0.194183
Vreal	V2	0.536258
Vreal	V3	0.529348
Vreal	V4	0.194233
Vreal	V5	0.169261
Vreal	V udec	0.279408

(B)

parameters		Mean square of differences
Vreal	V1	0.000428
Vreal	V2	0.000578
Vreal	V3	0.000574
Vreal	V4	0.000559
Vreal	V5	0.000535
Vreal	V udec	0.000563

3) Deep sections

This group includes sections with depths ranging from 30 to 45 meters. The correlation coefficients and mean squared differences are presented in Table 10. In this group, the first and fourth models exhibit a negative correlation (inverse relationship) of -0.53 with the actual grout intake. Similarly, the numerical model also shows an inverse linear relationship with a correlation coefficient of -0.44. The fifth analytical model is the only one that demonstrates a positive correlation (direct linear relationship) with the actual grout intake, with a correlation coefficient of 0.51. The second and third models show no correlation with the actual grout intake.

According to the results obtained using the mean squared difference method for comparing the models with actual grout intake in the deep sections, the fifth analytical model has the lowest error among all models. In contrast, the first model shows the highest error.

4) Very deep sections

This group includes sections with depths greater than 45 meters. The correlation coefficients and mean squared differences for this group are presented in Table 11.

The results presented in Table 11 indicate that, in the modeling conducted for the very deep sections, all models except for the fifth exhibit a positive correlation (direct linear relationship) with the actual grout intake, showing a relatively good level of agreement. Among them, the first and fourth models demonstrate the highest correlation. According to the mean squared difference analysis, the fourth analytical model achieves the best performance, with the lowest error, while the first model shows the highest error among all models in this group.

Subsequently, the trend of error variation in the analytical models was examined based on the mean squared difference values. The analysis revealed that as the depth of the grouting section increases, the modeling error also tends to increase. This trend is particularly evident in the first and third models, as illustrated in Fig.s 5 and 6.

Table 9. Comparison of calculated corrosion from analytical and numerical models with actual corrosion in sections with medium depth using: A- correlation coefficient and B- mean square of differences

(A)

Parameters		Correlation coefficient
Vreal	V1	0.102232
Vreal	V2	0.214871
Vreal	V3	0.214865
Vreal	V4	0.102154
Vreal	V5	-0.19603
Vreal	V udec	0.227037

(B)

Parameters		Mean square of differences
Vreal	V1	0.0007892
Vreal	V2	0.0011012
Vreal	V3	0.0010907
Vreal	V4	0.001069
Vreal	V5	0.001637
Vreal	V udec	0.001189

Table 10. Comparison of calculated corrosion from analytical and numerical models with actual corrosion in deep sections, using: A- correlation coefficient and B- mean square of differences

(A)

Parameters		Correlation coefficient
Vreal	V1	-0.53395
Vreal	V2	-0.23894
Vreal	V3	-0.24146
Vreal	V4	-0.53396
Vreal	V5	0.512753
Vreal	V udec	-0.43807

(B)

Parameters		Mean square of differences
Vreal	V1	0.003999
Vreal	V2	0.000838281
Vreal	V3	0.00083631
Vreal	V4	0.000783167
Vreal	V5	0.000532195
Vreal	V udec	0.000826642

Table 11. Comparison of calculated corrosion from analytical and numerical models with actual corrosion in very deep sections, using: A- Correlation coefficient and B- Mean square of differences

(A)

Parameters		Correlation coefficient
Vreal	V1	0.5644
Vreal	V2	0.521196
Vreal	V3	0.521571
Vreal	V4	0.564399
Vreal	V5	0.123273
Vreal	V udec	0.536832

(B)

Parameters		Mean square of differences
Vreal	V1	0.059274
Vreal	V2	0.004080464
Vreal	V3	0.00413514
Vreal	V4	0.00288181
Vreal	V5	0.007967331
Vreal	Vudec	0.003536781

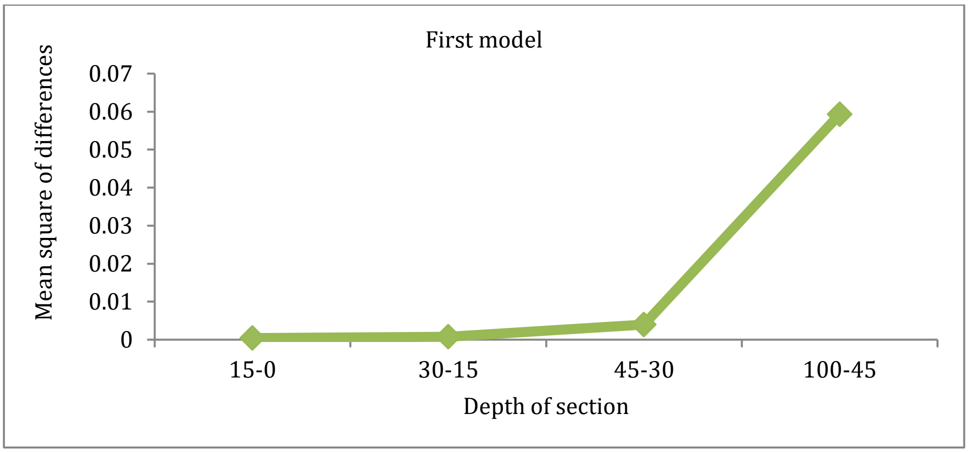

Fig. 5. Trend of increasing error in the first analytical model with increasing section depth

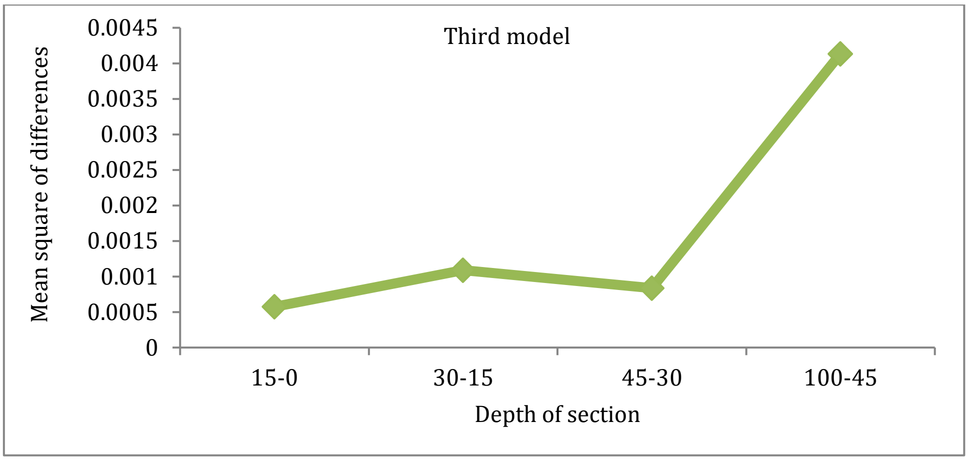

Fig. 6. Trend of increasing error in the third analytical model with increasing section depth

VI. Conclusions

This research introduced and investigated both analytical and numerical models for estimating the erosion (or loss) of cement slurry in grouting operations. To assess the accuracy and validate the models, statistical analysis methods were employed. Specifically, the correlation coefficient and the mean squared differences between the modeled and actual erosion values were calculated. Furthermore, the validation process considered two key parameters: the rock quality designation (RQD) and the depth of the grouting section.

Based on the rock mass quality, analysis of the correlation coefficients indicates that sections with excellent rock quality produce weaker correlations compared to sections with average quality, but stronger correlations than those with good quality. According to the mean squared differences, the fourth analytical model and the numerical model exhibit the lowest error among all the models evaluated. In contrast, the first and fifth analytical models show the highest error rates, indicating weaker performance. In all models except for the fifth the lowest modeling error is observed in sections with an RQD between 75–90. However, in the fifth model, the minimum error occurs in sections with an RQD between 50–75.

Based on the depth of the grouting section, in shallow sections, there is a correlation between the second and third models and the actual pore. According to the mean squared values of the differences, the first analytical model has the lowest error, and the second and third models have the highest error among the other models. In sections with medium depth, there is no correlation between any of the models and the actual pore. According to the mean squared values of the differences, the first analytical model has the lowest error, and the fifth analytical model has the weakest result. In deep sections, the fifth analytical model is the only model in this group that has a positive correlation (direct linear relationship) with the actual pore (0.51), and there is no correlation between the second and third models and the actual pore. In the comparative mean squared method, the fifth analytical model has the lowest error, and the first model has the highest error. In very deep sections, the first and fourth models have the highest correlation, and the fifth model has the weakest correlation with the actual pore. In the mean square difference method, the fourth analytical model provides the best result (least error) and the first model provides the most error. Also, the trend of increasing error of the models was examined based on the mean square difference values. The results showed that in general, with increasing depth of the grouting section, the error rate of the modeling increases.

Considering the total results obtained based on the rock quality parameters and the grouting section depth, analytical model 4 provides the best estimate of the grouting volume compared to other models. Because some models involve parameters that are not easily measured and are not available based on data obtained from grouting sites, the estimated grout volume from these models has lower accuracy compared to the actual grout volume. As a result, among the presented models, the fourth model estimates the volume of grouting with the least error. If only one model is considered, the fourth model is recommended.

Analytical model 5 provides the least accurate estimate of erosion among all the models studied. This is primarily due to the complexity of the parameters involved in its calculation and the model's sensitivity to those parameters. Since none of the models can fully account for all engineering and geotechnical geological conditions, the erosion estimates vary in accuracy across models. The second model is particularly sensitive to the rock quality, as the parameter a directly influences the calculated grout volume. Therefore, accurate identification of jointed rock is essential for reliable results using this model. The third model closely aligns with the second in both structure and results, producing similar erosion estimates. In this model, the length of contact between the borehole and the rock is a critical factor in determining grout volume. The fifth model, while more comprehensive, is also the most complex. It incorporates several variables, including detailed geological conditions of the rock mass and joints, differences in the penetration behavior of grout versus water, the curved flow path of the grout, and the influence of secondary circular joints. Because many of these parameters are difficult to measure accurately in the field, the fifth model exhibits the most significant error in estimating grout volume.

In general, the use of analytical models, particularly the fourth model, is recommended when a rapid estimate of grout volume is required, such as directly at the grouting site. Although this method may not offer the highest level of accuracy compared to more detailed estimation techniques, it provides a reasonably accurate approximation based on limited available information. Due to its low computational error and efficiency, the fourth analytical model is especially suitable for situations where time and data constraints exist.

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