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POROSITY ASSESSMENT IN ONE-DIMENSIONAL PERMEATION GROUTING USING SUSPENSION-TYPE GROUT SOLUTION

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ABSTRACT: Soil liquefaction, triggered by seismic activity, destabilizes loose and saturated ground leading to extensive damage. This research explores the application of permeation grouting as a mitigation technique for liquefaction. Grouting is a ground improvement technique that involves injecting grout solutions at low pressures into soil pores to enhance its properties. To promote sustainability, alternative materials to conventional cement-based grouts were proposed and demonstrated to be viable. Suspension-type grouts densify and solidify the ground, offering higher performance compared to solution-type grouts. However, a limitation of suspension-type grouts is the occurrence of clogging. As permeation progresses, porosity of the soil reduces, along with the performance of grouting. To evaluate the flow behavior and interaction of the grout to the soil, one-dimensional permeation tests using varying grout concentrations were conducted. The relationship between permeation pressure, permeation volume, and porosity of the soil was analyzed. Results demonstrated that densification happens as permeation volume and pressure increases. While beneficial for increasing liquefaction resistance, immediate densification impedes further grout permeation, reducing the improvement radius. Therefore, porosity assessment is critical in balancing densification and permeation volume. Numerical estimation using Kozeny-Carman equation was employed to model the porosity changes during permeation, and mean particle size was found to be a crucial parameter in the accuracy of the porosity estimation.

Keywords: Soil liquefaction, Permeation grouting, Suspension-type grout, Porosity assessment, Kozeny-Carman equation

1. INTRODUCTION

Amidst the continuous growth of cities and infrastructures, the field of geotechnical engineering becomes increasingly important as this serves as the foundation of every structure. Despite its apparent stability, the ground is composed of plates that are constantly in motion. When these plates collide, the immense force generated can lead to a sudden release of energy, resulting in an earthquake. The recent 2024 Noto Peninsula earthquake in Japan caused severe casualties and incurred several geotechnical-related disasters like slope failure and soil liquefaction.

Soil strength relies on intergranular contact forces (total stress). However, pore water pressure reduces this strength. Ground movement causes temporary excess pore water pressure, and when this equals or exceeds total stress, the soil liquefies, losing its load-bearing capacity. This liquefaction leads to significant ground consolidation, damaging infrastructure and impacting community safety and economic stability by blocking transportation.

Permeation grouting is one of many ground improvement methods that helps mitigate the risk of liquefaction. Grouting offers several advantages, like its simplicity, compact procedure, and minimal disturbance to the soil during improvement [1]. This makes it suitable for remediating existing foundations or to soil that cannot tolerate disturbance [2][3]. Grouting works by permeating a grout solution into the ground at low pressures. The solution consists of materials designed to improve the physical properties of the soil by means of densification and/or solidification. There are two types of solutions that are commonly used, solution-type and suspension-type. Compared to solution-type which uses liquid chemicals, suspension-type is a type of grout made with fine particles suspended in water. These particles are commonly composed of cement or pozzolans that solidify when activated, improving the properties of the soil its injected into. Suspension-type grouts offer higher versatility and generally develop greater strength due to particle densification, but estimating the quantity and area of improvement can be difficult, and particle clogging is a critical factor affecting performance [4].

1.1 Scope and Objective

Grouting is a three-dimensional ground improvement technique. As a first step for analyzing the permeation performance, one-dimensional permeation tests were conducted and analyzed. For the experiments, only one type of soil was used for all samples and were all in fully saturated condition prior to permeation. The study aims to assess the porosity changes of the soil throughout the permeation process using both experimental data and estimation.

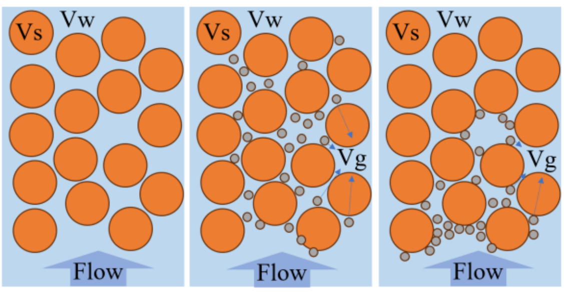
2. RESEARCH SIGNIFICANCE

Permeation grouting using suspension-type grouts has recently gained attention for its versatility and exceptional performance. However, the relationship between the grout material to its performance in grouting is not well backed. This study aims to establish a connection or understanding of the relationship between permeation pressure and changes in soil porosity based on both experimental and analytical results. By doing so, prediction of grout performance concerning other types of material or soil may be plausible.

3. CLOGGING MECHANISM

Clogging is a major problem concerning the permeation of suspension-type grout. Clogging happens when the particles suspended in the grout accumulates into the voids of the soil to a point where either the void space has been fully filled, or the pore throat becomes obstructed. Figure 1 shows three scenarios dealing with permeation grouting. V_s, V_w, and V_g depict the volumes occupied by the solid (soil), water, and grout respectively. Scenario (a) just shows the initial condition of the sample without any permeation. Scenario (b) shows the ideal grouting scenario, wherein the grout particles are evenly distributed throughout the voids of the soil sample. In contrast, scenario (c) shows the most realistic scenario that happens during permeation. The grout particles get trapped, or clogged in the direction of flow, hindering further permeation and resulting in uneven distribution of the grout particles within the voids of the soil. This also increases the flow resistance of the ground, thereby requiring increased permeation pressure to push grout particles deeper into the soil.

Clogging occurs erratically and it is difficult to pinpoint the exact locations. Several factors influence clogging, including soil type, relative density, pore throat size, particle size and shape, and many more. While difficult to pinpoint exactly, predictions can be made using external factors such as pressure and concentration or the amount of material injected into the pore spaces of the soil.



(a) (b) (c)

Fig. 1 Grouting illustration. (a): Soil only (b): Ideal scenario; (c): Clogging scenario

4. EXPERIMENTAL SETUP AND MATERIALS

One-dimensional permeation tests were done to analyze the flow of the grout during permeation. This was achieved using the apparatus shown in Fig. 2. The model soil height was 100 cm with a diameter of 5 cm, divided into 10 segments. Several water pressure sensors were installed along the column, at the inlet, 5 cm, 15 cm, 25 cm, 45 cm, and 75 cm away from the inlet. These sensors record the pressure as permeation commenced. Smaller increments were considered near the bottom as a non-linear pressure profile was expected within the soil.

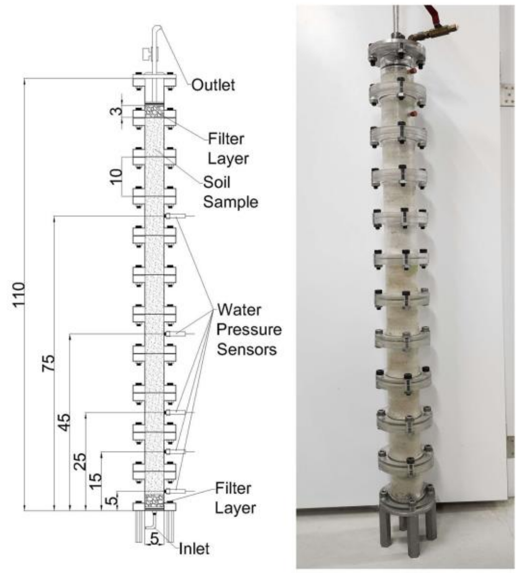


Fig. 2 One-dimensional permeation apparatus (in cm)

Silica sand #6 at a relative density of 60%, achieved through air pluviation, was used as the soil medium. After completion of the soil model and prior to permeation, the soil column was saturated with de-aired water at a very slow rate, avoiding any disruption, until a fully saturated condition was achieved. Grouting is a very complex procedure in which several factors influence performance. The grout material used for the permeation tests were ground-granulated blast furnace slag (BS) and calcium carbonate ($CaCO_3$) in a 1:1 ratio, by weight. As a suspension-type solution, it is necessary that the grout material used is several degrees finer than the soil particles [1]. The particle size distribution of the sand and grout materials used is shown in Fig 3. Varying concentrations were tested from 3%, 5%, and 7% powder-water ratio, also by weight. Permeation flowrate of 100 mL/min was deemed to be the optimal flow rate considering pressure developed and overall performance [1]. The permeation process was carried out until one of the following conditions was satisfied: (1) the pressure reached 400 kPa in the inlet ;(2) the pressure remained constant or (3) a sharp change in pressure was observed.

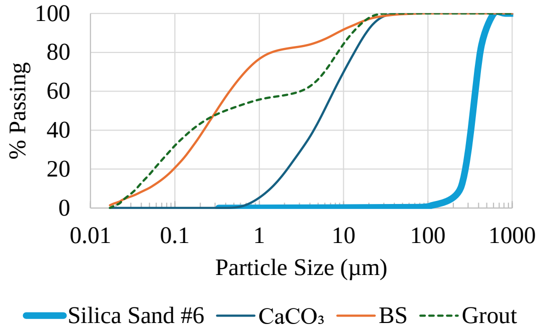


Fig. 3 Particle size analysis of the materials.

5. EXPERIMENTAL RESULTS

Permeation continued until one of the defined conditions was met. The amount of grout permeated as well as the grout retained within the soil column among the cases are summarized in Table 1. Despite having the most grout mass permeated, 7% concentration had a lower grout retention than 5% concentration. Grout retained means the amount of grout estimated to be retained within the voids of the soil. In the case of 7%, a higher expelled grout amount was observed, likely caused by soil fracture, creating a path of lesser resistance for the grout to pass through. This fracture can be further speculated from the pressure profile in Fig 4, as there was a sharp decrease in pressure.

Table 1 Grout injected amount per concentration

Case	1	2	3
Grout concentration	3%	5%	7%
Grout volume (L)	12.5	9.0	6.5
Dry grout injected (g)	375.0	450.0	455.0
Dry grout retained (g)	280.5	378.3	312.2
Dry grout expelled (g)	54.00	28.32	111.6
Loss (g)	40.48	43.37	31.23

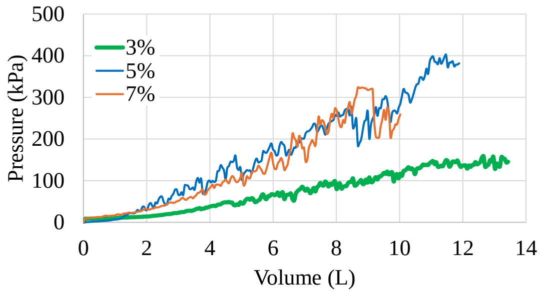
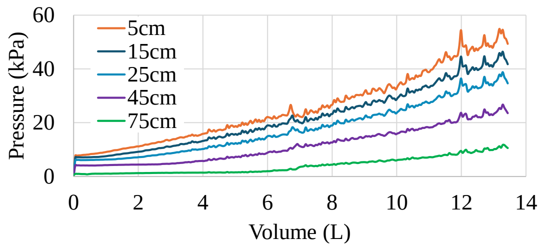


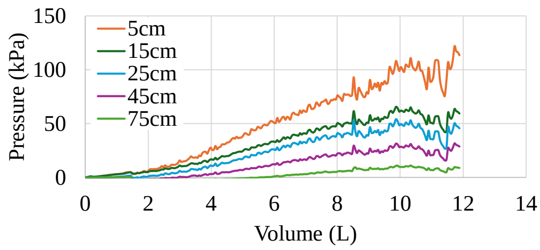
Fig. 4 Pressure at the inlet

5.1 Pressure Profile

As the permeation progressed, the pressures gradually rose in response to the volume of grout injected. This rise in pressure can be attributed to the reduction in pore spaces within the soil, which decreased its overall permeability. To compensate, higher pressure was needed to maintain a stable permeation rate. Fig. 5 presents the results of the permeation pressure to the volume of grout injected with varying concentrations. In all cases, pressure was higher near the inlet and decreased with distance. Apart from this, an almost linear pressure profile can be observed at each location as the permeation progressed. The pressure fluctuated erratically due to the continuous clogging and unclogging of grout particles. As these particles accumulate at specific points, the force required to push them increases, causing a temporary rise in pressure. Once pressure reaches the threshold needed to break apart the clumped particles, the pressure is abruptly released, causing pressure fluctuations.



(a)



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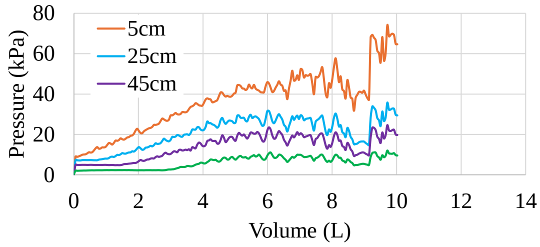


(c)

Fig. 5 Permeation pressure to the volume injected with varying concentrations: (a) 3%; (b) 5%; (c) 7%.

Fracturing of soil usually happens during high pressure permeation. While less common and usually at a smaller size, fracturing can also occur during low pressure permeations. A sharp decrease in pressure that does not recover back to the previous pressure generally means fracture occurred that lead to a path of lesser resistance for the grout to permeated into. Fracturing or cracking results in an uneven grout distribution, and lesser grout retention. Correlating this change to the amount of grout expelled a fracture was highly likely to have happened during the permeation. While fracturing is unavoidable and unpredictable, it is possible to know the moment it happens. This detection allows for adjustments or consideration of its impact on the overall grouting process.

5.2 Grout Distribution and Porosity

Following the permeation process, grout particle concentrations were measured at 10 cm intervals within the soil. Each segment was washed with water and sieved using a 75-micron sieve to allow the grout particles to pass through while retaining the sand. This process was repeated multiple times to maximize particle recovery. The resulting liquid was oven-dried, and the remaining powder was weighed to determine the final concentration. Fig. 6 compiles the grout retained in the soil per segment. For all cases, more grout retained in the part near the inlet and gradually lessens as the distance increases, albeit some uneven distributions.

Porosity is a fundamental parameter in permeation grouting, as it directly influences the effectiveness of grout flow and rate of soil densification. The initial porosity was computed to be 0.441, using the void ratio of silica sand #6 at a relative density of 60%. The post-permeation porosity of each segment was calculated and tallied in Table 2.

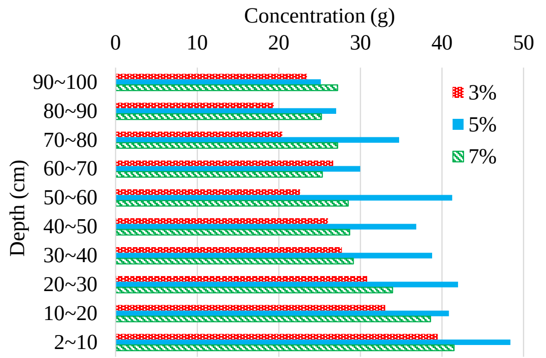


Fig. 6 Grout retained per segment per case

Table 2. Post-permeation porosity of each case

Position (cm)	Porosity		
	3%	5%	7%
90~100	0.399	0.396	0.393
80~90	0.407	0.393	0.396
70~80	0.405	0.379	0.393
60~70	0.394	0.388	0.396
50~60	0.401	0.368	0.390
40~50	0.395	0.375	0.390
30~40	0.392	0.372	0.389
20~30	0.386	0.366	0.381
10~20	0.382	0.368	0.372
2~10	0.353	0.333	0.349

Correlating the porosity data with the pressure data, an inversely related relationship can be observed from Fig. 7. From here, it can be observed that the higher the change in pressure results in a higher change in porosity. This can mean that each parameter influences the other in a direct manner. With this, predictions of porosity, and ultimately grout retained, can be made just by using the pressure data during the permeation process.

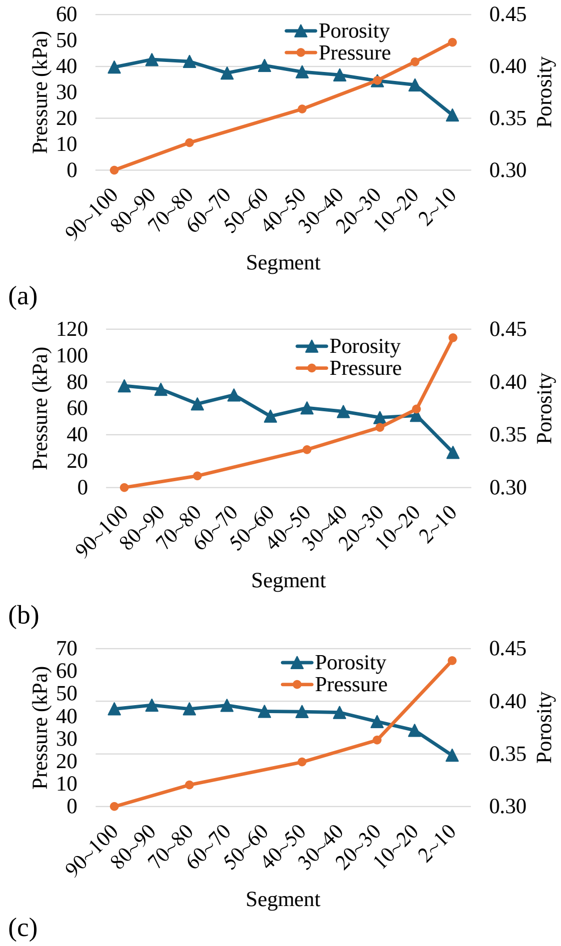


Fig. 7 Pressure and porosity with distance for varying concentrations: (a) 3%; (b) 5%; (c) 7%.

6. POROSITY ANALYSIS

Given the potential relationship between grout concentration or the porosity of the soil to the permeation pressure, numerical analysis serves as a powerful tool for optimizing permeation performance. This reduces the need for extensive physical testing which enhances the efficiency of grouting techniques. Numerical analysis was attempted to estimate soil porosity from permeation pressure incorporating factors such as pressure, depth, time, permeability, and particle size.

6.1 Quadratic Regression

Five pressure sensors were used in the permeation experiment with varying distances from the inlet. These determine the pressure change in the location of the sensor as the permeation commenced. To obtain a pressure profile of the soil column during permeation, quadratic regression was used.

$$P = ax^2 + bx + c \quad (1)$$

Where P is the pressure, x is the depth or the distance from the inlet. One function was created from one set of pressure data (from five sensors) per unit time (1Hz). Each function was able to achieve an r-squared value of around 0.95, signifying a high level of accuracy.

6.2 Darcy-Weisbach Equation

The energy of water flow comes from total head loss due to the frictional resistance on particles surfaces on both the soil and the grout [5]. Clogging further increases the required energy to flow. There are several ways to predict permeability using equations [6,7], Darcy-Weisbach is one of the commonly known equations to calculate for permeability. From the regression, pressure at any point in the soil column, at any point in time, can be estimated. As such, permeability using Eq. (2) at any place and time can also be calculated.

$$q = Ki \quad (2.1)$$

Where q is the flowrate in m^3/s, K is the hydraulic conductivity in m/s, and i is the hydraulic gradient. By altering some parameters, Eq. 2.2 can be derived from Eq. 2.1. This way, instead of the hydraulic gradient, the pressure gradient can be used.

$$q = \frac{k}{\mu}\left(\frac{dP}{dx}\right)A \quad (2.2)$$

Where k is the intrinsic permeability in m^2, μ is the viscosity in $kPa \cdot s$, dP/dx is the pressure gradient in kPa/m, and A is the area in m^2. Hydraulic conductivity and intrinsic permeability are commonly misunderstood and mixed up. Hydraulic conductivity is a function of both the soil and the fluid flowing through it, while intrinsic permeability is just a function of the soil or porous substance, independent of the fluid. [8,9]

6.3 Kozeny-Carman Equation

The Kozeny-Carman equation is an equation that relates permeability to its porosity, grain size, and tortuosity [9], shown in Eq. (3). It is a semitheoretical and semiempirical formula that is used to predict the permeability [5].

$$k = \frac{\theta^3 D_g^2}{72 * \alpha\,(1-\theta)^2} \quad (3)$$

Where θ is the porosity, D_g is the particle size, and α is the tortuosity and sphericity factor.

7. ANALYSIS RESULTS AND DISCUSSION

7.1 Parameters

As an attempt to estimate the porosity using pressure data, several assumptions were made, and some parameters were made constant. The soil medium was assumed to be fully uniform. Discharge velocity (or average velocity) was used instead of seepage velocity (or actual velocity). Tortuosity and sphericity factors were set to a constant value. The boundary conditions on porosity were set according to the maximum and minimum porosity recorded in the experiments conducted. Viscosity was taken from the viscosity of 5%, and since it did not significantly differ from 3% and 7%, it was assumed constant.

From Eq. (3), the particle size, D_g, was initially taken as constant, equal to the value of the 15% fraction of the soil, D_{15}. But an improved analysis was made with variable particle size that increased the accuracy of the estimation. Using both the particle size analysis of the sand and relating it to the amount of grout present, an empirical formula for D_g in mm as a function of porosity, shown in Eq. (4).

$$D_g = -0.0038 * \gamma_g(V_o(1-\theta) - V_{so}) + 0.2948 \quad (4)$$

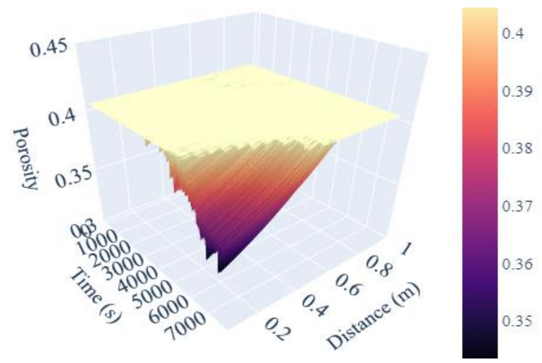
Where V_o is the total volume, V_{so} is the soil volume, both in cm^3, and γ_g is the density of the grout in g/cm^3.

7.2 Porosity Assessment

The porosity changes of the soil throughout the permeation process can be assessed with respect to both time (or volume injected) and distance (permeation radius). The initial porosity of the soil was 0.441, but an empirical factor for the upper boundary was used in the model that corrected the max porosity from 0.441 to 0.407. This factor was to account for the fine fraction of the grout particles that occupied pore spaces but were either small enough, or light enough not to incur any permeation pressure. Due to this, minimal changes in porosity were estimated near the starting time and towards the upper portions of the soil column. As the permeation commenced and more grout volume was permeated, grout particles deposited into the voids and resulted in a reduction of porosity.

There are two estimations done using the same process. The first attempt used a constant particle size equal to D_{15} and a constant factor in Eq. (3) of 180, which is the empirically accepted value in Kozeny-Carman equation. However, analysis using these assumptions led to a less accurate predictions of porosity. To improve the accuracy, a second attempt that involves a variable D_g, and a higher constant value of 300 was performed. The reason why the particle size was taken as a variable was because during permeation, the composition of the particles changed as more grout materials were permeated. Initially, the soil was composed of only sand, but during and after permeation, the soil also contained a portion of grout. This means that the mean particle size of the soil changes with the amount of grout permeated, which can be correlated with the porosity, hence necessitating the need for a variable D_g. Tortuosity can be hard to examine, but sand and granular materials typically exhibit a higher value [10], so a higher value was used.

Figs 8a and 8b show the result of the analysis of the first and second attempt of the 3% case, respectively. Fig 8a showed a smaller change in porosity during the initial stages and towards a higher distance (depth), while Fig 8b shows changes in porosity even during the initial stages of permeation. This can be understood as the effect or the inclusion of the grout material portion. On top of this, a shallower slope was also observed compared to Fig 8a, which is better representation of the grouting mechanism. Aside from the differences, both exhibited similar behaviors. The densest part of the soil sample was near the inlet (0 distance) and gradually reduced with distance. At the same time, porosity also reduces with time that corresponds to the amount of grout permeated. The more grout particles, the more it occupies the voids, the lower the porosity becomes.



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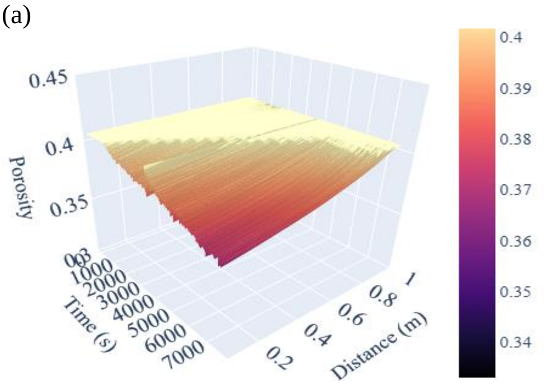
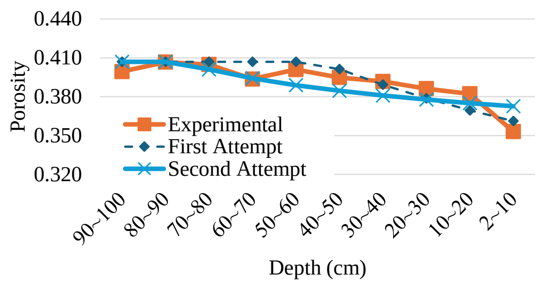


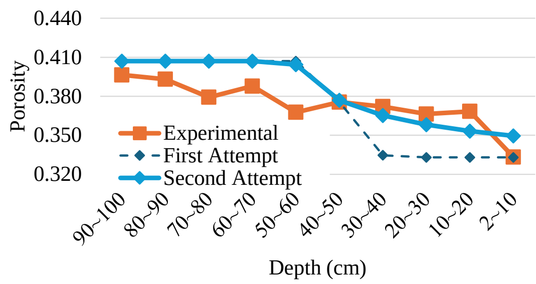
(b)

Fig 8. Porosity assessment of first (a) and second (b) attempt.

Post-permeation porosity estimated from using the analysis was compared with the experimental result and shown in Fig. 9. The estimated porosity was true to the assumption that the porosity was lowest near the inlet and gradually increases with distance. Both attempts show a similar relationship between experimental and analysis, proving that the process of estimation from the pressure data using Eqs (1-3) can be used. In the first attempt of estimating porosity with an assumed constant value of D_g, 3% concentration case had a good fitting but falls off at the 5% and 7% concentration cases. The slope obtained at the 5% case (see Fig 9b, first attempt) was too steep that may be due to the clogging of the particles that were not considered in the estimation using Eq. (3). The second attempt counted the changes in the particle size distribution due to the grout particles. The change of constant D_g to a variable D_g and increasing the tortuosity constant resulted in a shallower slope for all cases, which is more realistic in terms of one-dimensional permeation grouting.



(a)



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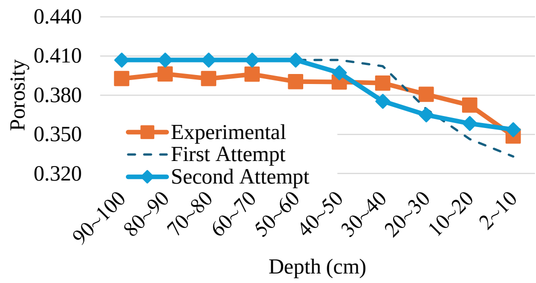

(c)

Fig. 9 Analysis and experimental comparison for various concentrations: (a) 3%; (b) 5%; (c) 7%.

To evaluate the accuracy the differences between the first and second attempts to the experimental data mean absolute error (MAE) shown in Eq. (5) and root mean square error (RMSE) shown in Eq. (6) were done. These quantifies the average difference between the predicted values and the actual observed values. MAE and RMSE are two standard metrics that are used to evaluate models and are widely adopted in many systems to measure the difference between predicted and actual values [11][12].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (6)$$

Where n is the number of data points in the sample, y_i is the actual (observed) value and $\hat{y}_i$ is the predicted value for the i-th data point.

The calculated value or the error of the porosity estimation to the actual experimental data are shown in Table 3. Simply, a smaller number of both MAE and RMSE values shows a better accuracy or better fit to the actual data. Except for 3% case, both 5% and 7% cases showed an improvement with the second attempt, as can be observed from the lower MAE and RMSE values. However, looking into the results of 3%, while showing a higher value of error, the slope of the curve (shown in Fig 9a, second attempt) had a better and more realistic approach. The first attempt had a better fit not because of a better estimation model, but rather because of the upper limit of porosity imposed. Without this limitation, the fitting would favor the second attempt more.

Table 3. MAE and RMSE values (porosity %)

Case	MAE		RMSE	
	First	Second	First	Second
3%	0.67%	0.81%	0.78%	0.97%
5%	2.17%	1.56%	2.60%	1.85%
7%	1.50%	1.23%	1.56%	1.28%

7.3 Discussion

The challenge faced with the initial attempt with an assumed constant particle size was the slope of the porosity change. From Eq. (3), one of the crucial factors was the particle size, D_g. In the first attempt, it was assumed to be constant using the size of D_{15}. This was used because in assessing the groutability of the grout solution, D_{15} was the particle size fraction used [1]. However, results showed that it was not a good fitting to the actual experimental data. Moreover, tortuosity increases with type of material and porosity [13][14]. Thus, a second attempt was performed trying to address the concern regarding the changing mean particle size. Using a variable D_g and an increased value of tortuosity, the accuracy was able to be improved as can be observed by the slope in Figs 8a to 8c and proven by the smaller MAE and RMSE values. While the value of MAE and RMSE in the 3% case seem to be worse than the first attempt, the second attempt was the better fitting between the two. Going back to the porosity prediction boundary, the upper and lower limit to the estimation were set to not overshoot and solve unusual porosity values. The upper limit was set empirically, accounting for the minute amount of grout material present within the voids, but not plenty enough to garner any permeation difficulties. As an analysis based primarily on pressure data, any amount of grout material less than the amount that induces pressure is taken as no grout present. Hence, needing empirical value or factor to account for this phenomenon. With the upper limit imposed, the overshot data from the first attempt was forcefully adhered to the limit, which was close to the actual porosity data obtained. In result, this created a falsely accurate fitting. On the other hand, the porosity estimated using the second attempt clearly showed a better profile, without much influence from the upper limit.

Aside from this, the second attempt of estimating the porosity using pressure data proved that the mean particle size distribution used in the analysis is a very important parameter and changing it from constant to variable substantially improved the accuracy of estimating porosity using pressure data. Yet, the estimation can be further improved by introducing some variability (like tortuosity and sphericity), and/or adding in another term to account for another factor not considered in the equations used.

Optimizing the model offers several advantages in permeation grouting. By knowing initial soil parameters like particle size from site investigation, the injected grout's composition (particle size and viscosity), and installing pressure sensors around the injection site, porosity changes during the grouting process can be predicted. This helps ensure proper coverage and allows for estimating the developed strength based on the grout concentration.

8. CONCLUSIONS

One-dimensional permeation experiments were conducted with different grout concentrations. As grout concentration increased, clogging rate became faster and fluctuations in permeation pressure were observed more frequently. Crucially, all tests revealed that permeation pressure constantly increased with permeated volume, that was caused by the clogging of the grout particles. This establishes an inverse relationship between permeation pressure and soil porosity. Furthermore, porosity change was greatest near the inlet and gradually decreased with distance.

An attempt to estimate the clogging mechanism or the changes in soil porosity was made, and the results reproduced similar trends to the experimental data. A second, improved model incorporated the changes in mean particle size distribution throughout the permeation process. MAE and RMSE metrics confirmed a significant improvement in model fit. The changes in mean particle size were found to be one of the most important factors to consider in estimating soil porosity.

Future work will focus on improving the accuracy of the model by including or altering some parameters to create a better fit and provide a more versatile model that can be used in a wider array of materials. Overall, conducting numerical analysis enables the estimation of porosity at any point in both time and distance during grouting.

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