Geomechanics and Engineering, *Vol. 17, No. 4 (2019) 367-374*
DOI: https://doi.org/10.12989/gae.2019.17.4.367

The observation of permeation grouting method as soil improvement technique with different grout flow models

Fatih Celik*

Department of Civil Engineering, Faculty of Engineering, Nigde Omer Halisdemir University, 51240 Nigde,Turkey

(Received March 6, 2018, Revised February 14, 2019, Accepted February 26, 2019)

Abstract. This study concluded the results of a research on the features of cement based permeation grout, based on some important grout parameters, such as the rheological properties (yield stress and viscosity), coefficient of permeability to grout (k_G) and the inject ability of cement grout (N and N_c assessment), which govern the performance of cement based permeation grouting in porous media. Due to the limited knowledge of these important grout parameters and other influencing factors (filtration pressure, rate and time of injection and the grout volume) used in the field work, the application of cement based permeation grouting is still largely a trial and error process in the current practice, especially in the local construction industry. It is seen possible to use simple formulas in order to select the injection parameters and to evaluate their inter-relationship, as well as to optimize injection spacing and times with respect to injection source dimensions and in-situ permeability. The validity of spherical and cylindrical flow model was not verified by any past research works covered in the literature review. Therefore, a theoretical investigation including grout flow models and significant grout parameters for the design of permeation grouting was conducted in this study. This two grout flow models were applied for three grout mixes prepared for w/c=0.75, w/c=1.00 and w/c=1.25 in this study. The relations between injection times, radius, pump pressure and flow rate for both flow models were investigated and the results were presented. Furthermore, in order to investigate these two flow model, some rheological properties of the grout mixes, particle size distribution of the cement used in this study and some geotechnical properties of the sand used in this work were defined and presented.

Keywords: permeation grout; spherical flow model; cylindrical flow model; inject ability of grout; rate of injection

1. Introduction

Grouting is known as the injection of fluid suspension materials into voids of the soil or space between the soil and contiguous structures. The main purposes of grouting are to generate a stronger, denser, and/or less permeable soil or rock; it can also easily work to fill voids, which may provide sufficient stress transfer within the soil or from a structure to the soil (Chang *et al.* 2016, Azadi *et al.* 2017). The permeation grout, which is an example of grouting technics, in porous media depends on stability (bleed capacity), filtration pressure, rheology (principally yield stress and plastic viscosity) and grain size distribution (Keong, 2005).

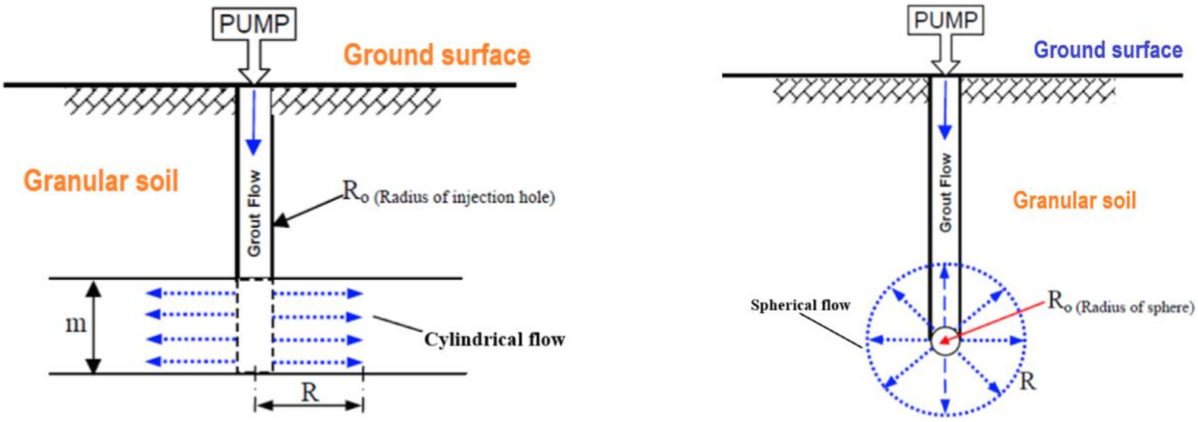
Permeation grouting is a technique in which the pore fluid is replaced (i.e., squeezed out) with grout injected at a steady injection without causing any change in the soil structure. As grout penetration depends on the permeability of the ground, the technique is generally restricted to clean sands and gravel or open fills that can be penetrated with low-viscosity grouts. Permeation grouting technique is generally used to reduce ground permeability and control ground water flow, but it can also be used to strengthen and stiffen the ground (Rawlings *et al.* 2000). Akbulut and Saglamer (2002) concluded that the soil particle size and the cement maximum particle size have important effects on the successful grouting. Anagnostopous (2005) has presented that the combination of such material with cement in grouting purpose with respect to water cement ratio contributes significantly to the improvement of grouted soil. As a general guide, it is difficult to permeate soils with a permeability coefficient (water) of less than 5×10^{-4} m/sec (Littlejohn, 1982) using ordinary cement grout (Portland Type I). Higher coefficient of permeability for water, i.e., above 5×10^{-3} m/sec as guide for cement based permeability grouting (Keong 2005). For the direct injection of grout into soil as in the process of permeation grouting, it is important to understand how the voids in the foundation soils are filled by the grout and which are the factors influencing the grout permeation.

Grout permeation through soil is usually related to the grout's permeability, measured in term of the coefficient of permeability (k_G) according to Darcy's law provided that the flow remains laminar. For a particular fluid, k is primarily a function of the void ratio, but particle size distribution, soil structure, saturation, and other factors also influence its value. Permeation in uniform soils follows a very regular form which may be correctly represented by simple mathematical models. These are usually based on either spherical or cylindrical flow model of Newtonian fluid (shown in Fig. 1) (Raffle and Greenwood 1961). Eqs. (1)-(4) derived from these two available models allow the estimation of pressure required for maintaining flow to a

*Corresponding author, Assistant Professor
E-mail: fatihcelik@ohu.edu.tr

http://www.techno-press.org/?journal=gae&subpage=7

ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Cylindrical (Radial) flow model (b) Spherical flow model

Fig. 1 Flow models for permeation grouting

given distance and injection hole spacing for permeation grouting as the function of the grout material parameters (viscosity and coefficient of permeability for grout, k_G, etc.) and grout method parameters (e.g., injection pressure and flow rate, etc.). Net pressure (P_e) in excess of local hydrostatic pressure necessary to maintain the flow from a spherical cavity of radius of R_o is a function of the grouting rate, the soil permeability and the viscosity of grout as expressed in the following relationship. According to Tomiolo (1982), these two available flow models consider the flow of viscous fluids through the soil follows the same laws ruling the flow of water (Raffle and Greenwood 1961), all values (coefficient of permeability to grout, k_G) being amplified proportionally to the ratio of grout viscosity to water viscosity (Muller 1972).

$$P_e = \frac{Q\gamma}{Ck_G} = \frac{Q\gamma\mu}{Ck\mu_w} \tag{1}$$

Net pressure for spherical flow (Raffle and Greenwood 1961)

$$t = \frac{4\pi n}{3Q}(R^3 - R_0^3) \tag{2}$$

Injection time for spherical flow (Raffle and Greenwood 1961)

$$P_e = \frac{Q\gamma\mu}{2\pi mk\mu_w} ln\left(\frac{R}{R_o}\right) \tag{3}$$

Net pressure for cylindrical flow (Raffle and Greenwood 1961)

$$t = \frac{\pi mn}{Q}(R^2 - R_0^2) \tag{4}$$

Injection time for cylindrical flow (Raffle and Greenwood 1961)

where; P_e= net pressure (kPa), Q= grouting flow rate (m^3/s), ɣ=unit weight of grout (kN/m^3), C=4πR_o (shape coefficient), k_G=permeability of soil to grout (m/s), k=permeability of soil to water (m/s), μ=plastic viscosity of grout (Pa.s), μw= viscosity of water (0,0015 Pa.s at 20°C), t= injection time (s), n= porosity of soil, m= thickness of injected grout layer (m), R= distance from grouting point (m) and R_o= radius of injection hole (m).

Permeability assessment therefore forms an important part of the investigation of inject ability of soils. In soils, empirical inject ability ratios, N=D_{15}/d_{85} and N_c= D_{10}/d_{95} can be used to assess the penetrability of particular grout (Michell 1981) as shown below.

N > 24 Successful grouting

N_c > 11 Cement grouting is consistently possible

N_c < 6 Cement grouting is not possible

where, D_{10}= 10% finer size from grain size distribution curve of soil, D_{15}= 15% finer size from grain size distribution curve of soil, d_{85}= 85% finer size from grain size distribution curve of cement, d_{95}= 95% finer size from grain size distribution curve of cement.

In the practical range of cement grout mixes for permeation grouting in ground improvement works, water/cement ratio for the cement grout mixes usually does not exceed 1.5 values (Helal and Krizek 1992). The influence of high injection pressure adopted in the permeation process to the flow characteristics is based on some important parameters such as the rheological properties (yield stress and viscosity) of various cement grout mixes and its flow characteristics. There are several studies that were conducted in the past studies based on theoretical and experimental researches related with permeation grouting (Helal and Krizek 1992, Houlsby 1990, Littlejohn 2003, Paoli *et al.* 1992, Krizek and Helal 1992, Perret *et al.* 2000, Lowther and Gabr 1997, Perret *et al.* 1997, Silva *et al.* 2016, Mirza *et al.* 2002, Jorne and Henriques 2016, Amnieh *et al.* 2017, Bohlolia *et al.* 2018), however the validity of these two grout flow models (spherical and cylindrical flow model) was not verified by any past research works covered in the literature review. It is possible, however, to use simple formulate to aid in the selection of injection parameters and to understand their inter-relationship, as well as to optimize injection spacing and times with respect to injection source dimensions and in-situ permeability. A better understanding of these parameters can help when it comes to calculating the real cost of an injection program and how to modify a scheme in progress to gain the best result. Therefore, a theoretical investigation including grout flow models and significant grout parameters for the design of permeation grouting was conducted in this study.

2. Experimental procedure

The methodology of the study was presented in Fig. 2 as following. According to this flow chart all methods and experimental programs were clearly observed.

2.1 Materials used in this study

In this study CEM I-42.5R Portland cement (PC) conforming to ASTM C150 Type-I cement was used. Table 1 presents the physical and chemical properties of cement used in this study. The particle size distributions curves of cement were plotted by using laser scattering technique and shown in Fig. 3. So as to evaluate the inject ability of the grout mixes 85% finer size from grain size distribution curve of cement (d_{85}) and 95% finer size from grain size distribution curve of cement (d_{95}) were estimated and presented in table 1. Poorly graded sand (SP) according to USCS (Unified Soil Classification System) was selected in this study for providing injectability of the grout mixes. Some geotechnical properties of the sand were presented in table 2. And also, particle grain size distribution curve of the sand was given in Fig. 3. According to this gradation curve of the sand, 10% finer size of the sand (D_{10}) and 15% finer size of the sand (D_{15}) were estimated and presented in Table 2 in order to assess the inject ability of the grout mixes in this study.

2.2 Mixture preparations and test methods

One of the significant parameters that have remarkable effect on hardened and fresh properties of grout mixtures is water-cement (w/c) ratio. Therefore, in this study different w/c ratios (0.75, 1.00 and 1.25) were selected to investigate the grout matrixes in the laboratory for representative determination of the important grout parameters. This range for w/c ratio is used for geotechnical applications such as cement grouts for soil or rock injection, jet-grouting and permeation grouting (Benhamou 1994). Three grout mixtures at various water-cement ratios were prepared for providing better simulation of the permeation process which was not properly considered in the practicing works and enhancing the application of such cement grout mixes in permeation grouting using the existing flow models which is a function of the grout properties (unit weight and viscosity) and the test parameters (injection pressure and grouting rate).

All mixes were prepared by using the same mixing method. A standard rotary type laboratory mixer that has 5 liter volume was used in order to prepare the grout mixes in this study. For all mixes, same standard methodology was applied and mentioned as following; the Portland cement was mixed with distilled water grouts were mixed with a Jiffy-type mixer at an angular speed of 2300 rpm. During the mixing process for all mixes, temperature and humidity were measured 23±3 and 55-65%, respectively. After the mixing process was completed, the rheological properties of grout mixes were estimated by using Coaxial rotating cylinder rheometer (pro-Rheo R180 Instrument, Germany). In order to compare the results, all tests were conducted in twice with new grout mixes and the test results were shown

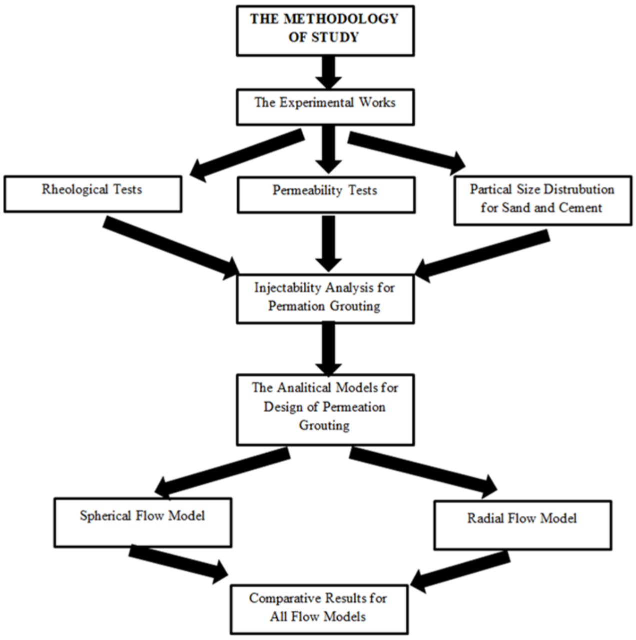


Fig. 2 The flow chart for methodology of the study

Table 1 Properties of the Portland cement used for this study

		Value
Chemical analysis (%)	CaO	61.94
	SiO_2	18.08
	Al_2O_3	5.58
	Fe_2O_3	2.43
	MgO	2.43
	SO_3	2.93
	K_2O	0.99
	Na_2O	0.18
	Loss on ignition	4.40
Physical properties	Specific gravity	3.17
	Fineness (Blaine)(cm^2/g)	3750
	d_{85} (85% finer size from grain size distribution curve of cement)	0.03
	d_{95} (95% finer size from grain size distribution curve of cement)	0.07

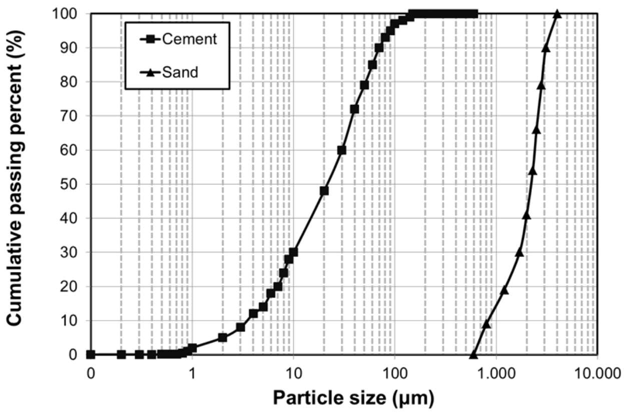


Fig. 3 Gradation curves of Portland cement and sand used for this study

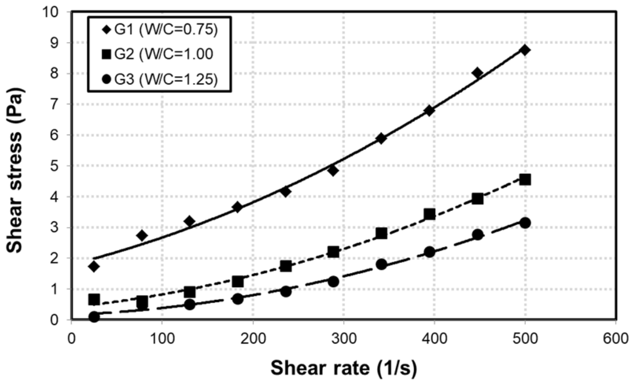


Fig. 4 Typical flow behavior of grouts obtained from the coaxial rheometer

Table 2 Apparent viscosity (Pa s) of grout mixtures at various shear rates

Mix ID	Shear rate (s^{-1})									
	50	100	150	200	250	300	350	400	450	500
G1	0,0520	0,0290	0,0220	0,0190	0,0175	0,0165	0,0175	0,0170	0,0180	0,0175
G2	0,0170	0,0068	0,0069	0,0070	0,0074	0,0077	0,0082	0,0088	0,0089	0,0091
G3	0,0063	0,0054	0,0036	0,0038	0,0040	0,0044	0,0054	0,0056	0,0062	0,0063

G1: Grout mix for 1st mode (w/b=0.75); G2: Grout mix for 2st mode (w/b=1.00); G2: Grout mix for 3rd mode (w/b=1.25)

Table 3 Fresh and workability features of the grout mixes

Mix ID	w/b	Density (g/cm^3)	τ_0 (Pa)	μ_p (Pa.s)	Grout Temperature (^0C)	R^2
G1	0.75	1.627	1.795	0.0070	20.0	0.994
G2	1.00	1.504	0.415	0.0030	24.1	0.995
G3	1.25	1.422	0.163	0.0020	23.7	0.992

τ_0: Yield stress; μ_p: Plastic viscosity

as repetitive.

Apparent viscosity, plastic viscosity and yield stress of mixes were estimated by using Coaxial rotating cylinder rheometer. Shear rates were selected as ranging from 25 s^{-1} to 500 s^{-1} for each grout mixes in this study. The ascending curves were obtained from flow curve depending on the shear stress–shear rate curve shown in Fig. 4. The shear-thickening behavior was observed with respect to the apparent viscosity of grouts for all grout mixes. Apparent viscosities and rheological properties obtained from the grout mixes at various shear rates were presented in Table 2 and Table 3. Any pre-shear method followed by a resting time at the beginning of the rheological measurements was not applied to the grout mixes.

In order to estimate the rheological features of the grouts, there are several types of analytical models. Bingham model that is one of them is commonly used for calculating the rheological properties of cement grouts (Yahia and Khayat, 2001). Plastic viscosity (μ_p) and yield stress (τ_0) are obtained from the shear stress versus shear rate curve. Moreover, if highly dilatant and shear thickening behaviors exists, the yield stress calculated by using the Bingham model is lower than true yield stress. Therefore, yield stress and plastic viscosity are calculated by using modified Bingham model. Modified Bingham model is described as second order polynomial equation and following Eq. (5) is given below (Yahia and Khayat 2001)

$$\tau = \tau_0 + \mu_p\dot{\gamma} + c\gamma^2 \quad (5)$$

where τ =shear stress (Pa), τ_0=yield stress (Pa), μ_p=plastic viscosity (Pa.s), $\dot{\gamma}$=shear rate (s^{-1}) and c=constant. The modified Bingham model presents a more certain solutions than the traditional Bingham model for the similar mixtures.

3. Results and discussions

Injection time (t), fluid plastic viscosity (μ), porosity of soil (n), permeability of soil (k), the injection pressure (P_e), injection source radius (R_o) and grout travel distance (R), thickness of injected grout layer (m) and flow rate of grout (Q) were evaluated according to two grout flow models (spherical and cylindrical flow model) and their relationships between each other were presented and discussed. Furthermore, Inject ability of the mixes was investigated and their results were presented in this part.

3.1 Inject ability of the mixes in this study

The result of analysis shows that 97% of the cement particles have a diameter smaller than 0.1 mm (100 µm) and the grain size distribution appears to be similar to that of the ordinary Type I Portland cement studied by (Schwartz and Krizek 1992). The values of d_{85} and d_{95} of cement grout are 0.03 mm and 0.07 mm, respectively. Moreover, the values of D_{10} and D_{15} of the sand are 0.80 mm and 1.00 mm, respectively. Therefore, empirical inject ability ratios, $N=D_{15}/d_{85}$ and $N_c= D_{10}/d_{95}$ were calculated in this study and N and N_c values were found as 33.33 and 11.43, respectively. As a result, it can be concluded that these mixes (G1, G2 and G3) are injectable for permeation grout applications according to an approach presented by Mitchell (1981).

3.2 Spherical flow model for permeation grouting

Fig. 5 shows Time-Radius relationships with respect to flow rate for spherical flow model when Eqn. (2) is used to examine the radius (distance from grouting point) based on injection time for a range of flow rate of grout, assuming the soil has a porosity of 0.45 and radius of injection hole (R_o) is 0.02 m. As it is clearly seen from Fig. 5, the selected flow rates are ranged between 0.01 m^3/s and 0.002 m^3/s.

These selected ranges are common values used for practical works for permeation grouting. According to Fig. 5, as injection time increases, the distance from grouting point (R) also shows a non-linear increase. Similarly, increase on amount of flow rate increases the distance from grouting point (R). These can be explained that; as the time of injection grout extends, much amount of grout permeates to the voids in the soil. Therefore, with respect to the porosity of soil, radius of the injected grout increases. The conclusion drawn from Fig. 5 is that, while an increase in

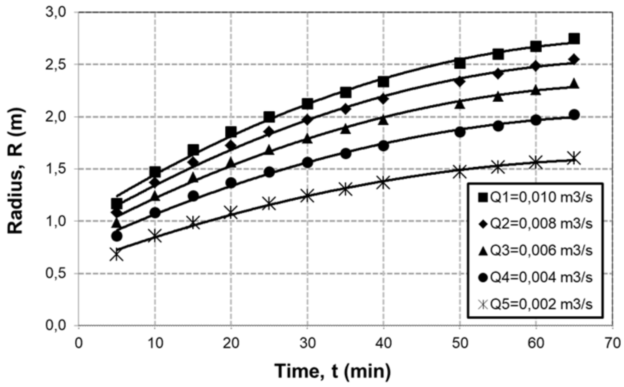


Fig. 5 Time-Radius relationships with respect to flow rate for spherical flow model

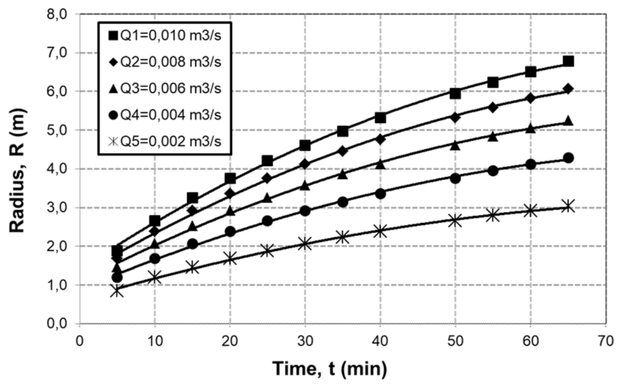


Fig. 7 Time-Radius relationships with respect to flow rate for radial flow model

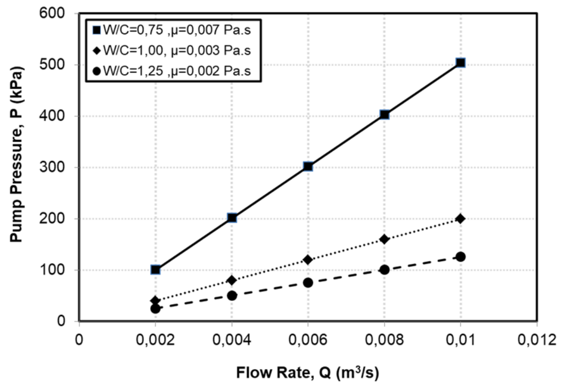


Fig. 6 Flow rate-pump pressure relationships with respect to w/c ratio or viscosity for spherical flow model

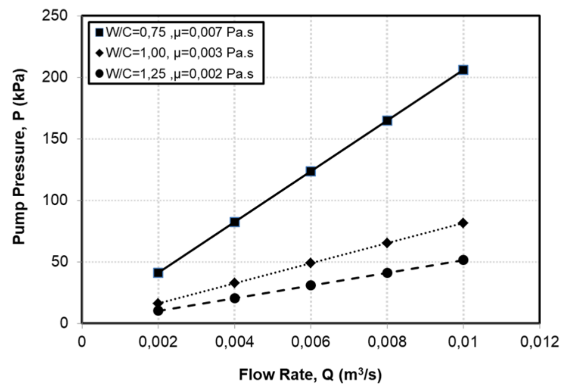


Fig. 8 Flow rate-pump pressure relationships with respect to w/c ratio or viscosity for radial (cylindrical) flow model

injection time is obviously beneficial with respect to an increase in the distance from grouting point (R), there appears to be an effective time cut-off point, as after 60 minutes the grout travel has reached nearly 70-80% of the distance possible in 2 hour (Hislam 2010).

Fig. 6 presents flow rate-pump pressure relationships with respect to w/c ratio or viscosity for spherical flow model when Eq. (1) is used to calculate the pump pressure (P_e) regarding on flow rate for a range of w/c ratio or plastic viscosity of grout, assuming the soil has a permeability of 0.006 m/s, viscosity of water at 20ºC is 0.0015 Pa.s and radius of injection hole (R_o) is 0.02 m. As concluded from Fig.6, the selected w/c ratios are ranged from 0.75 to 1.25. And also, the plastic viscosity values of the grout mixes for these w/c ratios are 0.007 Pa.s, 0.003 Pa.s and 0.002 Pa.s. These selected ranges of w/c ratios are common values used for practical works for permeation grouting (Raffle and Greenwood 1961, Helal and Krizek 1992, Fujii and Shimoda 1996). As clearly seen from Fig.6, there is a linear relation between pump pressure and flow rate for injection of the grouts in the permeation grouting work. An increase amount of flow rate increases the pump pressure linearly. On the other hand, while w/c ratio or plastic viscosity increases, pump pressure decreases. According to Fig.6, the estimated pressure difference between w/c=0.75 and w/c=1.25 at constant flow rate of 0.002 m^3/s is 76 kPa, whereas the estimated pressure difference for same w/c ratios at constant flow rate of 0.01 m^3/s is 378 kPa. Therefore, the conclusion drawn from this comparison is that; as the flow rate increases, estimated pressure difference raises growingly. The estimated pressure difference for flow rate of 0.01 m^3/s is nearly five times greater than that for flow rate of 0.002 m^3/s. It can be explained that, as flow rate of grout increases, the required pressure for pumping it increases.

3.3 Cylindrical (Radial) flow model for permeation grouting

Fig. 7 shows Time-Radius relationships with respect to flow rate for radial flow model when Eq. (4) is used to calculate the radius (distance from grouting point) based on injection time for a range of flow rate of grout, assuming the soil has a porosity of 0.45, thickness of injected grout layer is 0.6 meter and radius of injection hole (R_o) is 0.02 m. As drawn from Fig. 7, the selected flow rates are ranged between 0.01 m^3/s and 0.002 m^3/s. This selected flow rates are known values used for practical works for permeation grouting. According to Fig. 7, as injection time increases, the distance from grouting point (R) also shows a non-linear increase as same as spherical model. Similarly, increase on amount of flow rate increases the distance from grouting point (R). These can be explained that; as the time of injection grout extends, much amount of grout permeates to the voids in the soil. Therefore, with respect to the porosity of soil, radius of the injected grout increases. The conclusion drawn from Fig. 7 is that, while an increase in injection time is obviously beneficial with respect to an increase in the distance from grouting point (R), there also appears to be an effective time cut-off point similar to spherical flow model, as after 60 minutes the grout travel has reached nearly 70-80% of the distance possible in 2 hour (Hislam 2010).

Fig. 8 presents flow rate-pump pressure relationships with respect to w/c ratio or viscosity for radial (cylindrical) flow model when Eqn. (3) is used to calculate the pump pressure (P_e) regarding on flow rate for a range of w/c ratio or plastic viscosity of grout, assuming the soil has a permeability of 0.006 m/s, viscosity of water at 20°C is 0.0015 Pa.s, the distance from grouting point (R) is 2 meter and radius of injection hole (R_o) is 0.02 m. As concluded from Fig.8, the selected w/c ratios are ranged from 0.75 to 1.25. And also, the plastic viscosity values of the grout mixes for these w/c ratios are 0.007 Pa.s, 0.003 Pa.s and 0.002 Pa.s. As clearly seen from Fig. 8, there is a linear relation between pump pressure and flow rate for injection of the grouts in the permeation grouting work. An increase amount of flow rate increases the pump pressure linearly. On the other hand, while w/c ratio or plastic viscosity increases, pump pressure decreases. According to Fig. 8, the estimated pressure difference between w/c=0.75 and w/c=1.25 at constant flow rate of 0.002 m^3/s is 31 kPa, whereas the estimated pressure difference for same w/c ratios at constant flow rate of 0.01 m^3/s is 155 kPa. Therefore, the conclusion drawn from this comparison is that; as the flow rate increases, estimated pressure difference raises growingly. The estimated pressure difference for flow rate of 0.01 m^3/s is nearly five times greater than that for flow rate of 0.002 m^3/s as same as spherical flow model. It can be explained that, as flow rate of grout increases, the required pressure for pumping it increases.

Fig. 9 shows thickness of injected grout layer-radius relationships with respect to flow rate for radial (cylindrical) flow model. The non-linear relations between thickness of injected grout layer and the distance from grouting point (R) are clearly seen from Fig. 9. According to this figure, as the thickness of injected grout layer increases, the distance from grouting point dramatically decreases up to m=0.6 meter for all flow rates given in the study. When the thickness of injected grout layer (m) is greater than 0.6 meter, the distance from grouting point (R) is not to change any more and to stay constant. This reduction can be explained that the voids existing in the ground increases with respect to increasing the thickness of injected grout layer (m). Therefore, these voids filled with injected grout in vertical direction. As a result of that injected grout may not spread to voids in horizontal direction and the distance from grouting point (R) may not increase any more. Furthermore, at constant thickness of injected grout layer (m) as flow rate increases, the distance from grouting point (R) increases (see Fig. 9). Thickness of injected grout layer-Radius relationships with respect time for radial flow model is presented in Fig. 10. The similar behavior is also observed for Fig. 10. At constant thickness of injected grout layer (m) as injection time increases, the distance from grouting point (R) increases (see Fig. 10). The main reason of this can be explained as; increasing of injection time raises cumulative amount of grout in ground and this causes remarkable increasing in the distance from grouting point (R).

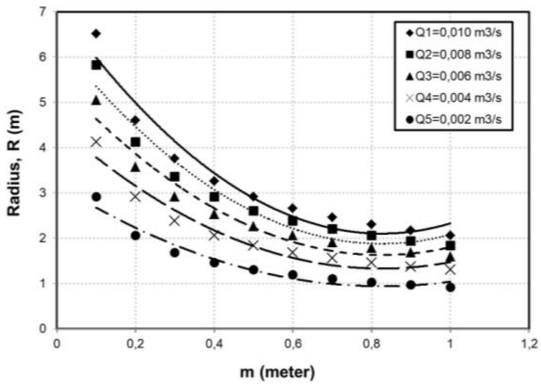


Fig. 9 Thickness of injected grout layer-Radius relationships with respect flow rate for radial flow model

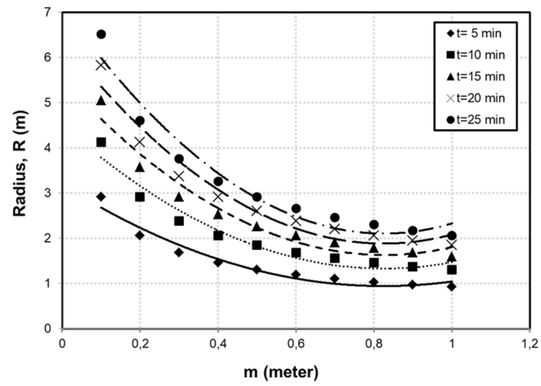


Fig. 10 Thickness of injected grout layer -Radius relationships with respect time for radial flow model

3.4 Comparison of cylindrical (radial) and spherical flow models for permeation grouting

The primary theories of permeation grouting include spherical flow model and cylindrical flow model. Based on these models, researchers presented many computational formulae about the grout diffusion Radius (Peng *et al.* 2011) Spherical and cylindrical flow model formulas are applicable to Newtonian fluid. Considering influence of gravity on grout permeation, grout diffusion in practice works was usually based on cylindrical flow model (Peng *et al.* 2011). The results showed that the value of computing radius based on cylindrical flow model is slightly larger than the one based on spherical flow model. According to Peng *et al.* (2011), the difference among this model might be caused by the influence of gravity on grout permeation. Moreover, under all same conditions in order to inject grout to the ground in same flow rate, more pumps pressure is needed for spherical flow model than cylindrical flow model (see Figs. 6 and 8).

4. Conclusions

This study concluded the results of a research on the features of cement based permeation grout, based on some important grout parameters, such as the rheological properties (yield stress and viscosity), coefficient of permeability to grout (k_G) and the inject ability of cement grout (N and N_c assessment), which govern the performance of cement based permeation grouting in porous media. Therefore, a theoretical investigation including grout flow models and significant grout parameters for the design of permeation grouting was conducted in this study. The conclusions that can be drawn from this study are presented as followings;

• These mixes prepared for this study are injectable for permeation grout applications with respect to fine particle diameters of the cement and the sand.

• Furthermore, while an increase in injection time is obviously beneficial with respect to an increase in the distance from grouting point (R), there appears to be an effective time cut-off point, as after 60 minutes the grout travel has reached nearly 70-80% of the distance possible in 2 hours for both flow models.

• And also, when the thickness of injected grout layer (m) is greater than 0.6 meter, the distance from grouting point (R) is not to change any more and to stay constant.

• Injected grout may not spread to voids in horizontal direction and the distance from grouting point (R) may not increase any more.

• Finally, the value of computing radius based on cylindrical flow model is slightly larger than the one based on spherical flow model. The difference among these models might be caused by the influence of gravity on grout permeation.

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