Journal of Civil Engineering (IEB), 33 (2) (2005) 105-118

Journal of
Civil Engineering
IEB

Estimation of injection rate and solidified shape in permeation grouting in sandy soil

M. Kamal Uddin

Institute of Appropriate Technology
Bangladesh University of Engineering and Technology
Dhaka 1000, Bangladesh

Received on14 February 2005

Abstract

In the process of chemical grouting in sandy ground, permeation grouting technique is usually applied. When the IR is in the higher range, a fracturing in the ground occurs. Such fracturing inhibits the process of permeation grouting. A relationship exists between the IP and IR for a ground that depends on other factors, e.g. soil type, viscosity of grout, ground condition, etc. This paper is a part of a comprehensive research program recently conducted wherein attention is focused on the shape characteristics of the solidified grouted mass with effect of variability of the IP, injection time, rate of injection and gel time. Laboratory and field injection tests were carried out in order to find out the relationships among the IP, IR, injection time and some other pertinent variables such as long or short gel time. Whether or not the IR is suitable for permeation grouting can be predicted with the method described in the paper.

Keywords: Injection rate, Injection pressure, shape, sand, soil.

1. Introduction

Permeation grouting corresponds to pressure grouting with the aim of filling the pores between soil particles. There is essentially no change in the volume or structure of the original ground. The permeation grout generally used is either a particulate suspension, (i.e., a suspension in water of cement, bentonite) or a chemical gel, e.g., sodium silicate. Particulate grouts are made up of cement, soil or clay particles. Mixtures of these chemical grouts are composed of various materials in solution. Permeation grouting creates satisfactory solidified shape in the grouted soil mass area. However, if the IR crosses an allowable boundary value, fracturing is initiated in the ground and the grout flow is channelized through cracks. This way, the pores between the soil particles of the soil mass is not filled up properly by the grout and it becomes impossible to solidify the desired injection area. In such a case, effect of grouting is greatly reduced and permeation grouting becomes impossible. Satisfactory grouting is essentially indicated by the solidified shape of the desired injected soil mass (Mori, et al, 1992).

Since the solidified shape of the desired injected soil mass is a prime criterion for successful permeation grouting in a ground improvement scheme, it is of utmost importance to know about the allowable IR that ensures the creation of appropriate solidified shape of the injected soil mass (Miki, 1973). In order to find out a correlation between the injected shape and injected rate, field injection tests were carried out. The field tests were conducted in fine to medium sand layer at a suburb area of Dhaka city, Bangladesh. Chemical grout was chosen for the study as it offers an advantage over the particulate grouts, because chemical grout can penetrate smaller pores of fine sand.

2. Permeation grouting and the relationship between IP and IR Characteristics of the study area

An important relationship exists between IP (IP) and IR (IR) while injecting chemical grout into a sand deposit. From the relationship, a device can be formulated to obtain the boundary of IR that will ensure appropriate permeation grouting. That means whether the applied rate of injection is able to produce permeation grouting can be predictable from the relationship. A typical relationship between IP and IR (IP-IR curve) is shown in Fig. 1. The relationship can be obtained by injecting chemical grout stepwisely into a sandy medium through a hole. The IP shown in Fig. 1 is that under constant IR. At the initial stage of the injection process, the IP remains in the lower range. In this portion of injection, the grout percolates into the pores of the soil mass and gradual increment of IR will enhance IP. At this stage, the fluid flows in the soil medium and a linear relationship exists between IR and IP (Shimada et al., 1993). The flow follows Darcy's law, i.e., the superficial velocity of flow is directly related to the pressure gradient. Thus at initial stage, during stepwise increase of IP, the IR is directly proportional to IP. This linear relationship corresponds to perfect permeation grouting. The gradient of the linear relationship depends on viscosity of grout, permeability of soil, diameter of the injection hole and soil type.

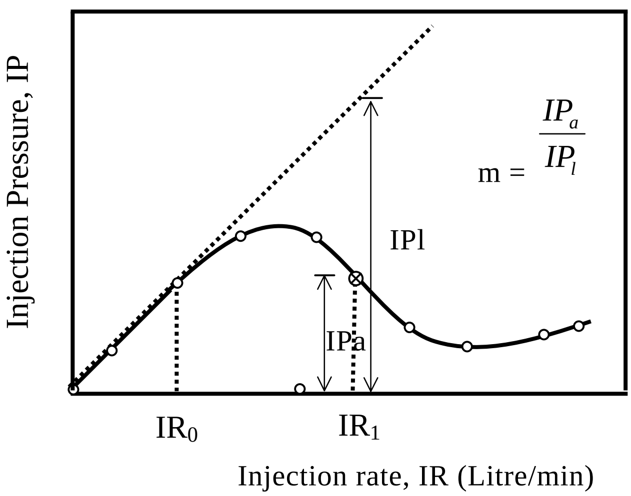

Fig. 1. Relationship between the IP and the IR(Shimada et al., 1993)

The linear relationship continues up to a value (IR0), after that the IP deviates from linearity. After reaching peak, the pressure would not be increasing with further increment of IR rather the pressure would be receding. A stage is attained when the soil mass reaches a boundary value designed as IRcrit (Fig. 1) when fracturing is initiated in the soil medium and the grout fluid moves along the fractured surfaces and it does not contribute to the pressure enhancement. Thus IRcrit refers to a momentous boundary limit with respect to permeation. With further increase of IR, fracturing continues to initiate in various forms and IP reduces gradually. Fracturing in the soil mass hinders formation of solidified shape of the injected mass as grout can penetrate into the soil through the fractured surfaces. After fracturing, the injected soil mass partially solidifies in various irregular shapes and depends on number, size, type and extent of fracturing. Therefore, permeation grouting is not possible when fracturing propagates in the injected area. Thus a satisfactory solidified shape of the soil mass is an indication of permeation grouting. A successful permeation grouting produces approximately spherical shape of the solidified injected mass. Therefore, the satisfactory solidified shape, which is approximately spherical, may be obtained when fracturing does not initiate or does not extend to or stops near injection hole. If the number of fracture is more and/or sizes of fractures are large, then the IP reduces sharply with increase of IR as shown in Fig. 1. In such case, it is quite impossible to get a desirable solidified shape of the grouted mass. At any stage of injection process, the degree of permeation is denoted by m (Fig. 1). The value of m can be defined by

$$m = \frac{IP_a}{IP_l} \tag{1}$$

Where,
IPa = Value of IP as per actual test at any stage of IR.
IPl = Value of IP as per linear relationship at the same stage of IR.

In Fig. 1, the value of m defined by equation (1) is shown when the IR is (IR)1. The extent of permeation is reflected in the value of m. Perfect grouting is possible if the value of m is equal to 1. The permeation grouting thereby solidified shape becomes worse as the value of m decreases from 1. It is important to know the allowable minimum value of m in order to achieve permeation grouting. Thus the first onus is to determine the allowable value of m. If in a chemical grouting process, the value of m is less than its allowable value, it can be understood that fracturing has been developed in the soil mass and the proper solidified shape and thereby perfect permeation is not possible. The allowable value of m can be determined from laboratory model test.

3. Grout used in the tests

A sodium silicate based grout with organic reactant was used in the tests. Sodium silicate based grouts are basically composed of two different components. These components are main gel base and reactant. Grouts are classified according to the type of main gel base and reactant. The main gel base of the grout used in the test was sodium silicate solution. Organic reactant (glyoxal) was used for sodium silicate solution. The solution type of grout was used, because it can penetrate all kinds of sands from coarse to fine. On the other hand, suspension types of grouts are limited in penetration and depend on particle size. Two kinds of sand (fine and medium) were stabilized by permeation of sodium silicate grout enriched with organic reactant glyoxal in the laboratory. Miki et al. (1973) used similar grout and process in the tests. The properties of sands are shown in Table 1. The properties of grout are shown in Table 2.

Table 1
Properties of Sands Used for Stabilization to Investigate Effectiveness of the Grout.

Sand	Grain Size (mm)	Gs	Void Ratio emax	Void Ratio emin
Fine sand	0.074~0.42	2.67	0.93	0.68
Medium sand	0.074~2.00	2.68	0.92	0.52

3.1 *Strength of Stabilized Sand and Grout Gel*

The unconfined compression tests were conducted to obtain the strength of stabilized sand and grout gel after curing for 1 week at room temperature 22°C and humidity varying from 90-100%. Three gel times were used, namely short gel time = 10 second, Medium gel time = 10 minutes and long gel time = 60 minutes. The purpose of the tests was to determine the relationship between strength and gel time. For each grouting case, the density of sand remained constant. Thus from the result, the strength of gel and the strength of stabilized sand can be compared independently over the varying time periods. The result is shown in Table 3.

Table 2
Properties of Grout (Sodium Silicate + Organic Reactant)

Composition	Sodium silicate solution	Glyoxal	Water
Ratio	100	30	70
Volume	500 cc	150 cc	350 cc
S102 Content	0.25 gm/cm3		
Strength of Solid Mass		976 kPa	
Gel Time		10 min.	

Note: Sodium Silicate and Sodium Alkali Ratio = 3

Table 3
Unconfined Compressive Strength of Stabilized Sand and Grout Gel (Sodium Silicate with Organic Reactant Glyoxal)

Gel Time	Strength of Stabilized Sand (kPa)	Strength of Gel (kPa)
Short	721	255
Medium	607	225
Long	569	130

4. Laboratory model test to find allowable value of m

A comprehensive study on permeation grouting was done by the author in Asian Institute of Technology, Pathumthani, Bangkok, Thailand during 1995-97. The Model Tests of Grouting by injection in sand were performed in the laboratory to find the allowable value of m using the relationship between IR and IP. In a big-sized injection tank, the injection tests were performed; sodium silicate grout of varying quantities was injected in sand. The relations among IR, IP and solidified shape were found out. From the result, it was evident that the allowable value of m is contingent on the viscosity of the grout and size of the injection hole. Ordinary long gel time grout having viscosity of 1.8 cps (contipoise) was used. Long gel time of 60 minutes and injection hole of diameter 1.5 " (38.1 mm) with height 4" (101.6mm) were used. Calculated values of m were correlated with the solidified shapes produced in various injection tests. It was found that the allowable value of m was approximately 0.35 corresponding to allowable value IR (i.e. IRcrit).

5. Water injection test

Water injection tests were carried out in the field with a view to establish the IP-IR relationship. From a cylindrical hole diameter 1.5" (38.1 mm) and height 4" (101.6 mm), water was injected into the ground (Fig. 2). From the test, the relationship between IR and IP was established. This relationship (IP-IR curve) obtained from water injection test was used for predicting solidified shape in the actual field tests. In the field test, the solidified shape thus predicted was compared with the actual solidified shape obtained after excavation.

6. Field test

A site at Turag sandy plain at the outskirt of Dhaka city in Bangladesh was chosen for the field test [field test location plan provided in Fig. 5 (b)] . The sodium silicate grout was injected to fine to medium sand with different IRs. Soil profile of the ground is shown in Fig. 3. The soil properties are shown in Table 4. Uniform sand of (fine to medium) layer encountered from -4m level up to the higher depth. The grout was injected at depth of 5m and 7m. The grain size distribution curves are shown in Fig. 4.

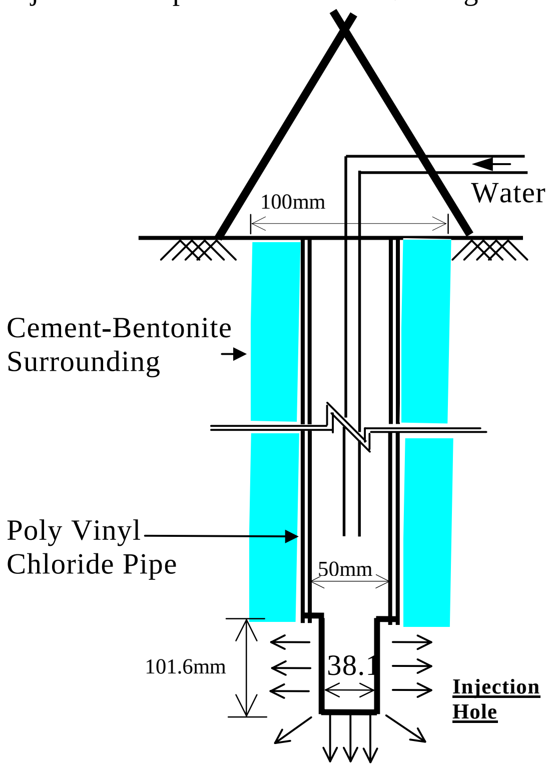

Fig. 2. Water injection test

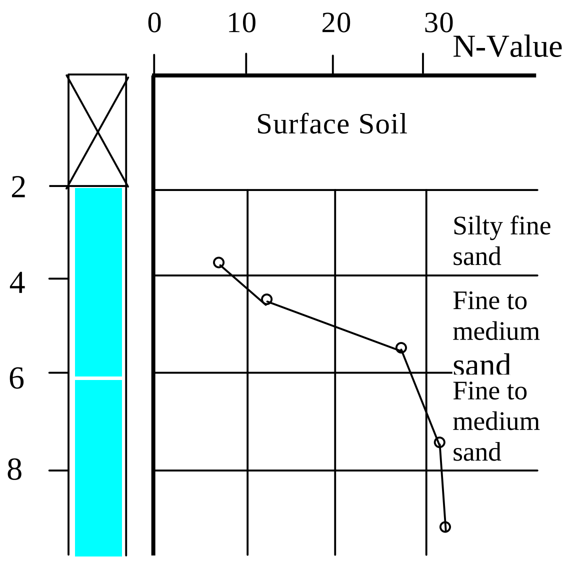

Fig. 3.Soil profile

The layout of injection points is shown in Fig. 5 (a). Five injected holes were made. In total sixty injection tests were carried out at five locations as shown in Fig. 5, at depth of 5m and 7m at each location. Table 5 shows the details of the injection tests.

Table 4
Soil Properties

Depth	Soil Type	Dry Density (kN/m3)	Permeability (cm/see)	N-value
2.5-4m	Gray, medium plasticity, silly sand	14.80	1.3-3	5-10
4-5m	Fine to medium sand	14.90	1.0-4	8-20
5-8m	Fine to medium sand	15.10	1.0-4	20-33

Table 5
Details of Injection Tests

Depth (m)	Designation of Injection Tests					Comments	
	Location A	Location B	Location C	Location D	Location E	IR	Kind of Grout Gel Time
5	A5-3-S	B5-3-S	C5-3-S	D5-3-S	E5-3-S	IR=3 lit/min	Short Gel Time
	A5-8-S	B5-8-S	C5-8-S	D5-8-S	E5-8-S	IR=8 lit/min	
	A5-24-S	B5-24-S	C5-24-S	D5-24-S	E5-24-S	IR=24 lit/min	
	A5-3-L	B5-3-L	C5-3-L	D5-3-L	E5-3-L	IR=3 lit/min	Long Gel Time
	A5-8-L	B5-8-L	C5-8-L	D5-8-L	E5-8-L	IR=8 lit/min	
	A5-24-L	B5-24-L	C5-24-L	D5-24-L	E5-24-L	IR=24 lit/min	
7	A7-3-S	B7-3-S	C7-3-S	D7-3-S	E7-3-S	IR=3 lit/min	Short Gel Time
	A7-8-S	B7-8-S	C7-8-S	D7-8-S	E7-8-S	IR=8 lit/min	
	A7-24-S	B7-24-S	C7-24-S	D7-24-S	E7-24-S	IR=24 lit/min	
	A7-3-L	B7-3-L	C7-3-L	D7-3-L	E7-3-L	IR=3 lit/min	Long Gel Time
	A7-8-L	B7-8-L	C7-8-L	D7-8-L	E7-8-L	IR=8 lit/min	
	A7-24-L	B7-24-L	C7-24-L	D7-24-L	E7-24-L	IR=24 lit/min	

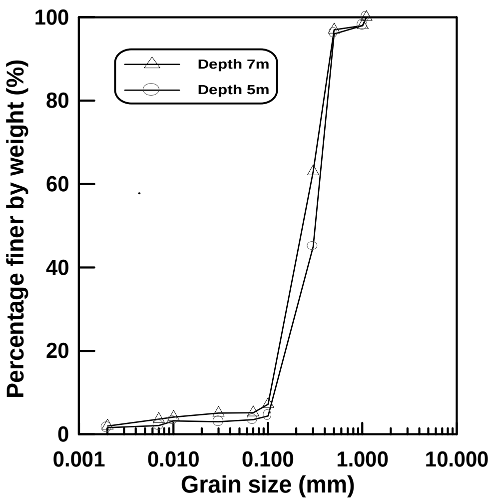

Fig. 4. Grain Size Distribution

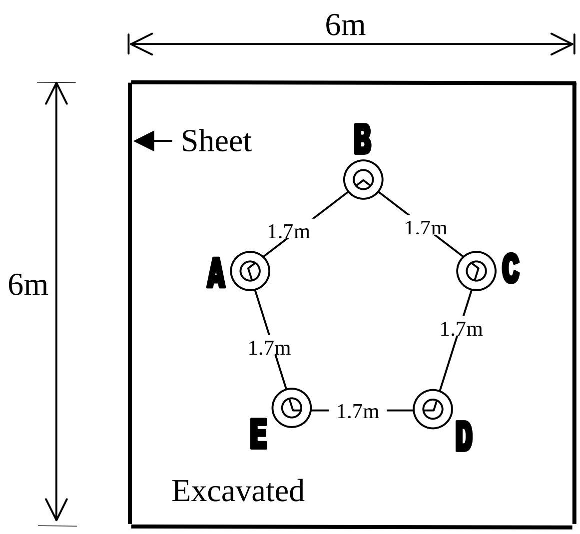

Fig. 5 (a). Layout of Injection

The total injection volume in each case was 120 litres in all cases. Three kinds of IR were used to inject grout, namely 3 litres/min, 8 litre/min, and 24 litres/min. The used grout was sodium silicate based gout with organic reactant glyoxal (discussed before).

Two types of grout were used. One was the long gel time grout whose gel time was approximately 60 minutes. The other one was short gel time grout whose gel time was 5 seconds. After injection, the solidified bodies were excavated and the shapes were recorded in details.

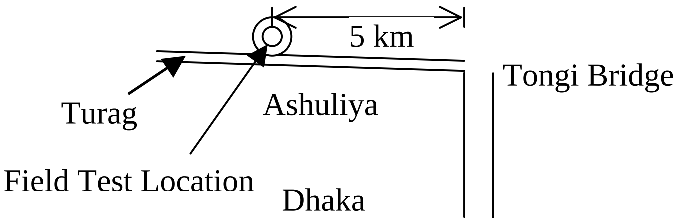

Fig. 5 (b). Field Test Location Plan

7. Test results

7.1 IP-IR curves from water injection tests

Water injection tests were carried out at 5m and 7m depth. Fig. 6 shows the IP-IR curves for 5m and 7m depths. The configuration of the used hole for water injection tests is shown in Fig. 2. From the laboratory model test, it was found that in order to achieve permeation grouting, the allowable value of m should not be more than 0.35. From the results of water injection tests, it can be found that the allowable IR (IRcrit) when value of m is 0.35, are 15 litres/min and 19 litres/min for depth 5m and 7m respectively. The paramount criterion to achieve satisfactory solidified shape is low IR, which should not be higher than the IRcrit. The IR 24 litres/min is larger than the IRcrit for both 5m and 7m depth. Thus it can be predicted that an IR of 24 litre/min would initiate fracturing and the solidified shape is expected not to be of satisfactory shape. On the other hand, permeation grouting is expected when the IR is at lower range such as 3 litres/min and 8 litres/min at 5m and 7m depth. Secondly, the gel time is another factor for satisfactory permeation. Long gel time produces better spherical shape than the short gel time.

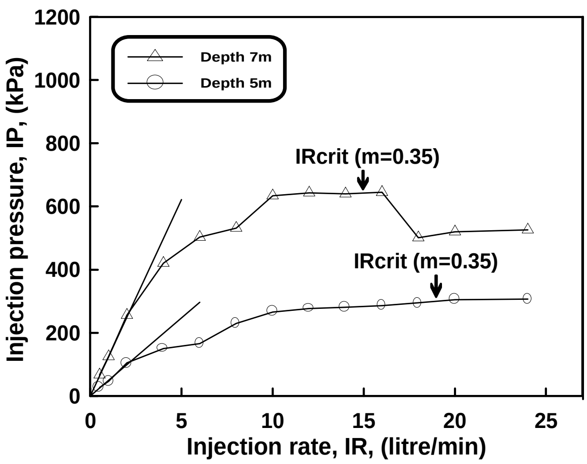

Fig. 6. Water Injection Tests: IR-IP Relationship

7.2 Solidified shape of grouted mass: long gel time

After the field test, the solidified masses were extracted by excavation. The solidified shapes for the injection tests: A5-3-L, B5-8-L and D5-24-L are shown in Fig. 7, 8, & 9. All these cases belong to long gel time grouting at 5m depth. The IRs were 3 litres/min, 8 litres/min and 24 litres/min respectively. In the case of 3 litres/min (A5-3-L) and 8 litres/min (B5-K-L) of IR, the solidified shapes were found satisfactory and of round shape. The IRs in these two tests were less than IRcrit. On the other hand, solidified shape for the test D5-24-L in which IR was 24 litres/min, was not spherical. The extracted grouted mass was of flaky shape. For this sample, the permeation grouting was not possible, because the IR was higher than IRcrit (15 litres/min). Thus it is seen that these three samples comply with the shapes predicted from IP-IR curves obtained from water injection tests (Fig. 6).

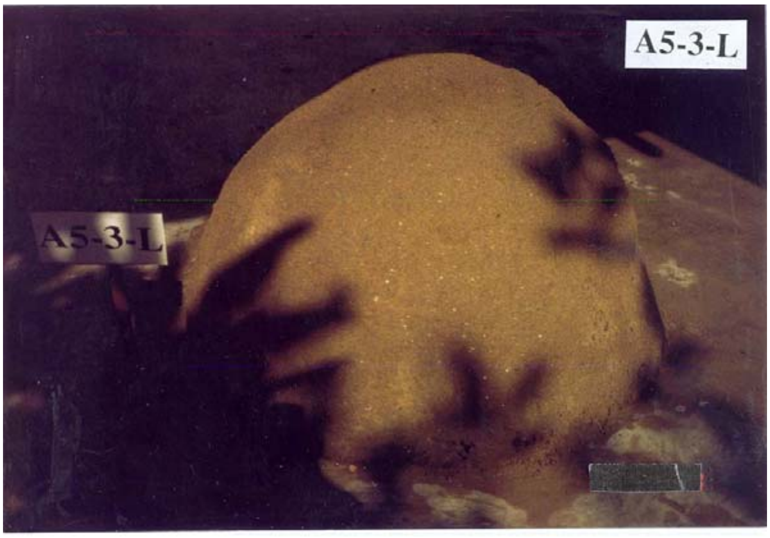

Fig. 7. Case A5-3-L: Solidified Shape

7.3 Solidified shape of grouted mass short gel time

Figures 10 and 11 show the solidified shape in the case of C5-8-S of C7-8-S. The solidified shapes in these two cases are flaky or plank-shaped. The solidified shapes of these two grouted masses resemble the shape of D-5-24-L (Fig. 9). For the test cases C5-8-S and C7-8-S (Fig. 10 & 11), short gel time grout was used and the IR was 8 litres/min. Though the IR was less than IRcrit, the grouting could not produce permeation grouting and thereby a satisfactory solidified shape was not possible owing to use of short get time grout. Fig. 12 shows the test case E7-24-S which shows that the solidified shape is not satisfactory at all. This is due to use of short gel time grout as well as higher IR.

7.4 Solidified shape of grouted mass: long + short gel time

Fig. 13 shows the solidified shape of the test case D7-8, where the grout injected at 7m depth with 8 litres/min IR. In this case, 60 litres of the long gel time grout was injected at the first stage. After that 60 litres of long gel time, grout was injected at second stage.

The solidified shapes in the case of D7-8 (Fig. 13) were better than those of the cases of C5-8-S, C7-8-S or E7-24-S, where totally short time gel grout was used.

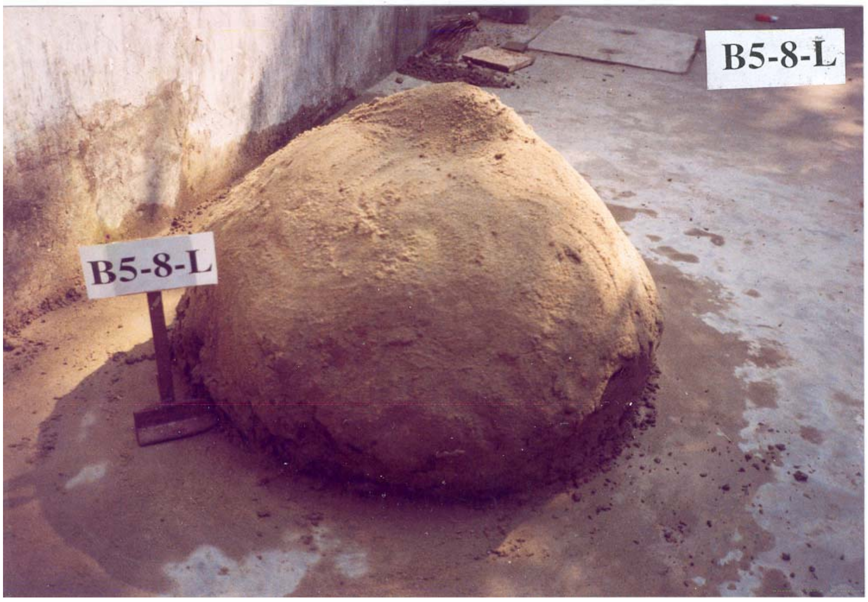

Fig. 8. Case B5-8-L: Solidified Shape

Fig. 9. Case D5-24-L: Solidified Shape

Fig. 10. Case C5-8-S: Solidified Shape

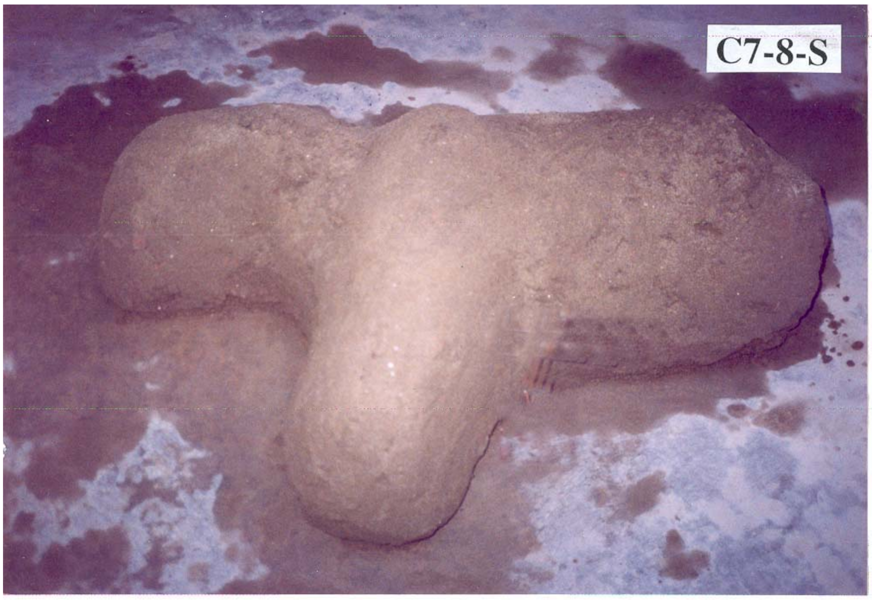

Fig. 11. Case C7-8-S: Solidified Shape

The solidified shape pertaining to long time gel grout is approximately spherical as shown in test cases A5-3-L, B5-8-L, (Fig. 7 & 8). Thus it is seen that the solidified shape becomes more spherical as the ratio of long gel time grout to total injection grout increases.

Fig. 12 Case E7-24-S: Solidified Shape

Fig. 13 Case D7-8: Solidified Shape

7.5 Relationship between IP and injection time

The relationship between IP and injection time in the test cases of A5-3-L, B5-8-L and D5-24-L is appended in Fig. 14. The figure shows that the case (D5-24-L) with highest IR (24 litres/min) rendered highest IP. On the other hand, IP was lowest for the lowest

IR (3 litres/min) (test case A5-3-L). Thus it is seen that higher the value of IR, higher the pressure it renders. Fig. 15 shows the relationship of test cases A7-8-L, D7-8, C5-8-S (all IR=8 litres/min). Comparison is made in the Fig. among long, short and long + short gel time grout.

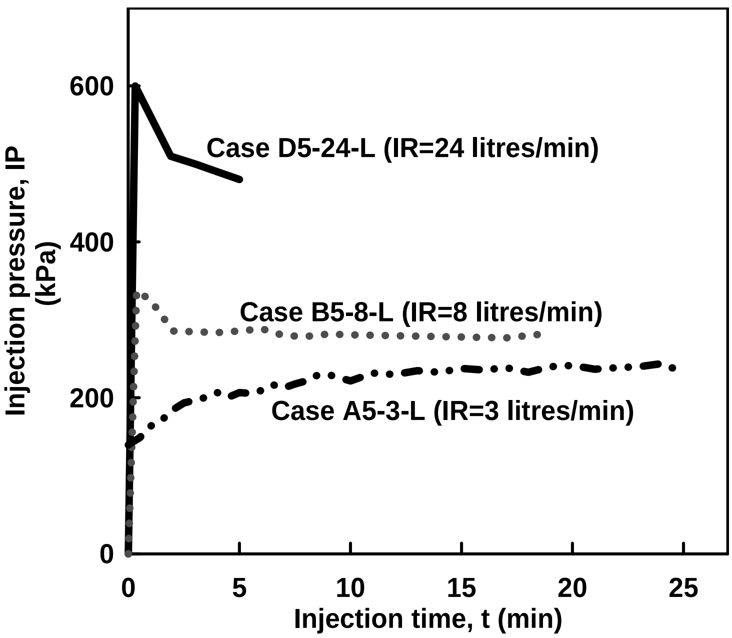

Fig. 14. IP-Injection Time Relationships (Long Grout)

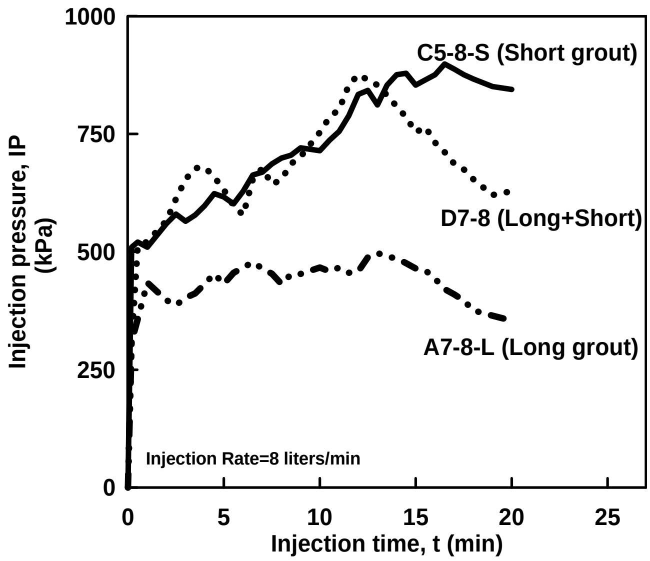

Fig. 15. IP-Injection Time Relationships (Long + Shot Grout)

7.6 Relationships of solidified weight

Table 6 shows the weights of solidified grouted masses extracted. Apparently, it seems that no relationship or trend exists among the solidified weights. The weight of the grouted masses ranged from 839 kg to 1382 kg.

7.7 Chemical quantitative analysis to find grout volume in total pore volume

In order to determine the ratio of grout volume to total pore volume, the weight of solica in the solidified sand was measured by chemical quantitative analysis. It was seen that if the pores of the soil were perfectly filled with the injected grout, the solidified weight would be in the order of 600 kg. But the weight measured was much larger than the value calculated. Thus it is evident that the grout could not fill the pore of the soil properly. Thus the solidified volume was much larger than the volume calculated. The quantitative analysis showed that the ratio of silica varied from 55% to 67%.

Table 6
Weight of Solidified Grouted Mass Extracted

Weight of the Solidified Mass									
Location A		Location B		Location C		Location D		Location E	
Tests	Wt. (kg)	Tests	Wt (kg)	Tests	Wt. (kg)	Tests	Wt. (kg)	Tests	Wt. (kg)
A5-3-S	1107	B5-3-S	987	C5-3-S	1105	D5-3-S	1209	E5-3-S	1011
A5-8-S	1049	B5-8-S	1120	C5-8-S	989	D5-8-S	1322	E5-8-S	978
A5-24-S	948	B5-24-S	1234	C5-24-S	1098	D5-24-S	1145	E5-24-S	1149
A5-3-L	1063	B5-3-L	1289	C5-3-L	1302	D5-3-L	1012	E5-3-L	1209
A5-8-L	1195	B5-8-L	1027	C5-8-L	1045	D5-8-L	1096	E5-8-L	1283
A5-24-L	1045	B5-24-L	1178	C5-24-L	1018	D5-24-L	1190	E5-24-L	1145
A7-3-S	839	B7-3-S	1323	C7-3-S	998	D7-3-S	1278	E7-3-S	898
A7-8-S	1076	B7-8-S	1362	C7-8-S	1239	D7-8-S	1196	E7-8-S	919
A7-24-S	1309	B7-24-S	1238	C7-24-S	1056	D7-24-S	986	E7-24-S	1018
A7-3-L	1044	B7-3-L	1109	C7-3-L	1295	D7-3-L	1301	E7-3-L	1298
A7-8-L	1298	B7-8-L	1256	C7-8-L	1034	D7-8-L	1298	E7-8-L	1309
A7-24-L	1134	B7-24-L	1289	C7-24-L	1382	D7-24-L	1123	E7-24-L	1299

8. Conclusions

The solidified shape characteristics of a grouted mass is an indicator for permeation grouting. Satisfactory solidified shape thereby perfect permeation grouting with the long gel time grout is contingent upon the IR. In this paper, a method is presented for predicting IR for permeation grouting. When the IR is greater than the value of critical IR (IRcrit), it is impossible to achieve satisfactory solidified shape. The value of IRcrit is determined by allowable value of m, which was determined from laboratory model test. IRcrit value can be determined from IP-IR curves obtained from water injection test in field. A number of field injection tests were conducted and the predicted shapes were compared with the grouted masses extracted by excavation. The predictions were correct for almost all the cases. Moreover, the paper focuses the influence of gel time as well. The long gel time grout has positive affect in filling the pores in the grouting process leading to permeation grouting while short gel time grout was found to produce frail and inconsistent solidified matrix. Some sort of trends were noticed in relationship among various parameters such as IP, injection time, IR and gel time which have been presented in the paper.

References

Mori, A., Tamura, M., Shibata, H. and Hayashi, H. (1992). Some factors related to injected shape in chemical grouting, Special Congress, Grouting, ground improvement and geosynthetic, ASCE, New Olreans.

Miki, G., (1973), Chemical stabilization of sandy soils by grouting in Japan, Proc. 8th ICSMFE, (4.3), 395.

Shimada, S., and Yonekura, R., (1993), New Chemical Injection Method, 11th Southeast Asian Geotechnical Conference, 1993, Singapore, pp. 403-408.