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Laboratory Study of Grouting Method to Improve Loose Sand Against Liquefaction

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ABSTRACT Liquefaction is a phenomenon when soil behaves like liquid during earthquake, and only occurs in saturated loose fine sand with grain size ranging from 0.2 to 0.02 mm. Liquefaction can be devastating, causing failure and deformation to buildings, roads, and bridges. Thus, research study on the application of grouting method for improving liquefiable fine sand in the laboratory is carried out. Grouting is a soil improvement method that injects cementing agent into a soil mass. After the grout has solidified, the soil density and consistency of the soil will improve. This research proves, mathematically and experimentally, that grouting can improve the density and consistency of liquefiable sand, thus reducing the liquefaction potential. Grouting liquefiable saturated sand basically compacts the soil, leading to consolidation as soil pore-water is dissipated during the grouting process. It is found that the volume of grout per unit volume of soil mass treated is directly proportional with the reduction of void ratio and increase in soil density.

KEYWORDS Liquefaction; Grouting; Void Ratio; Density

1 INTRODUCTION

Indonesia is one of the places on earth with high earthquake activity. This is because the territory of Indonesia is located at the confluence of four major tectonic plates, namely the Eurasian, Indo-Australian, Pacific, and Philippine plates. The confluence of these plates resulted in tectonic mechanisms and geological conditions of Indonesia becoming very complicated (Simanjuntak, 1994). One of the damaging events induced by earthquake is liquefaction. Soil liquefaction generally occurs in fine sand with loose and saturated conditions (Seed & Idriss, 1971). When there is earthquake vibration, saturated loose fine sand soil tends to densify, causing excess pore-water pressure to develop. If the excess pore-water pressure is not dissipated quick enough, it is possible for the pore-water pressure to reach a value nearing or equal to the overburden pressure. When this happens, the effective stress in the soil approaches zero, making it lose most of its shear strength. At that time the soil is said to have undergone liquefaction. Liquefaction is usually accompanied by occurrence of piping.

Efforts to mitigate liquefaction are usually carried out by increasing the density of the soils. For instance, by using the Dynamic Compaction and Vibro Compaction methods. However, these two methods of soil improvement are suitable for large scale project and both require large headroom. For small projects and places with small headroom, e.g., warehouse, grouting operation may offer an interesting alternative for improving the density of liquefiable soils.

2 GROUTING

Grouting is a process of injecting cementing liquid into soil and/or rock formations. The cementing liquid will then bind and harden. Grouting has the aim of:

- increasing density
- reducing permeability
- reducing compressibility
- increasing shear strength

Based on its flow pattern, the grouting method can be categorized to permeation and non-permeation grouting.

2.1 Permeation Grouting

Permeation Grouting is when the grouting liquid fills the soil pores or rock gaps with minimum influence on the original structure and there is no change in soil volume. Grout liquid can cover the grains of soil or fill the discontinuity of rocks masses. Permeation grouting is usually carried out for water retaining structure projects such as weir or dams, with the aim of reducing water seepage and reducing the compressibility of the foundation soil.

2.2 Non-permeation Grouting

Non-permeation grouting is when the grouting liquid is injected into the soil mass, the grout displaces or mix with the surrounding soil mass, increasing its density and consistency. Non-permeation grouting can be further categorized into Compensation Grouting and Soil Mixing. Compensation grouting has the purpose of compacting the soil mass by injecting grout liquid with a certain viscosity. Grout liquid will displace and compact the surrounding soil. Grouting compensation is generally used to overcome the problems of foundation settlement of buildings, subsidence due to tunnel construction and compacting soil mass that has the potential for liquefaction. As for soil mixing, jet grouting or augers are used to mix in-situ soil at designated depth with binder (cement, lime, slag, or other binders). Soil mixing can be carried out with wet or dry method.

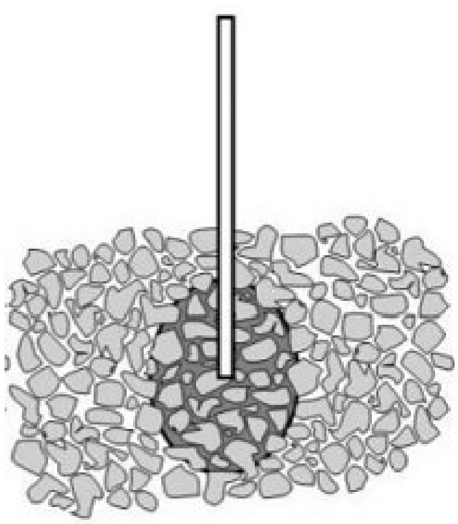

Figure 1. Permeation grouting pattern

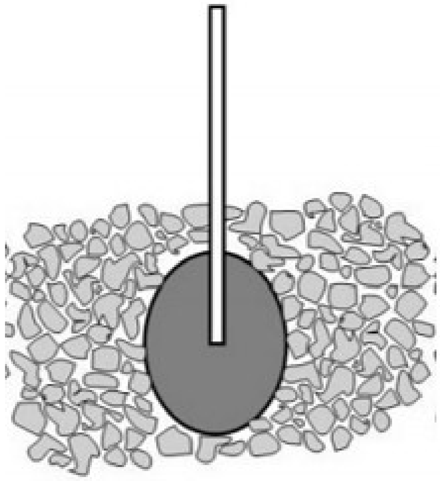

Figure 2. Non-permeation grouting pattern

2.3 Grout Material

The selection of grouting material depends on the consistency of the soil and the improvement results required after grouting. Grouting materials come in two forms, one of them is suspension that contain particles, while the second one is in the form of diluted chemical solutions (Shroff, 2009).

Including cement, suspension grouting materials also contain sand, loam, stone ash, fly-ash, and bentonite clay. In suspension grouting, the grouting ability depends on its viscosity and the ratio of the particle size in the suspension to the size of the pore opening or fractures of the rock mass.

Chemical solution grouting materials include silicates, lignosulphonate, amyloplasts, acrylates, epoxy resins, polyester resins, polyurethane, and other resin chemicals. In chemical grouting, the grout ability is a function of liquid viscosity and freezing time (gel time).

The criteria for the particle size of effective grouting materials are:

a) Ground pore openings must be 3x the diameter of grouting particles to be free from clogging (Raffle and Greenwood, 1961)
b) Grout can freely flow into soil pore when the diameter of the grouting particles is less than 1/15 of the soil particles being grouted (King and Bush, 1961).
c) The diameter of the grouting particles < 0.1 D_{10} (Bell, 1982)
d) Kravetz, 1958 mentions D_{15}/D_{85} = 5 - 24
e) King and Bush, 1961 suggest $D_{15}/D_{85} > 16$
f) Mitchell, 1970 suggested $D_{15}/D_{85} > 25$

Note: D_{10}, D_{15} and D_{85} refers to the grain size corresponding to 10, 15 and 85 percent finer, respectively.

In addition to the grain size of the grouting material, the viscosity of the grouting material is also an important factor in the effectiveness of grouting in improving soil and rock formations.

3 GROUTING MODEL DEVELOPMENT

Direct grouting injection can increase the density of the soil being grouted. The grout liquid that displaces the soil will solidify and occupy part of the existing soil volume. Thus, grouting method can be one of the effective alternatives for compacting soil. This is especially true for loose fine sand which has the liquefaction potential.

Some researchers have tried to mathematically formulate the compaction effect of grouting. One of them is *Al-Alusi (1997),* in his paper *"Compaction Grouting from Practice to Theory".* The Al-Alusi model was developed to explain the mechanism of soil compaction during grouting operation. For homogeneous and isotropic soils, the grouting pressure in the soil mass is assumed to be spherical with a center at the tip of the injection pipe. On the outermost border of the sphere, the stress and disturbance due to grouting injection pressure are equal to zero or so-called neutral boundary. Further, the stress and strain conditions that occur are as follows.

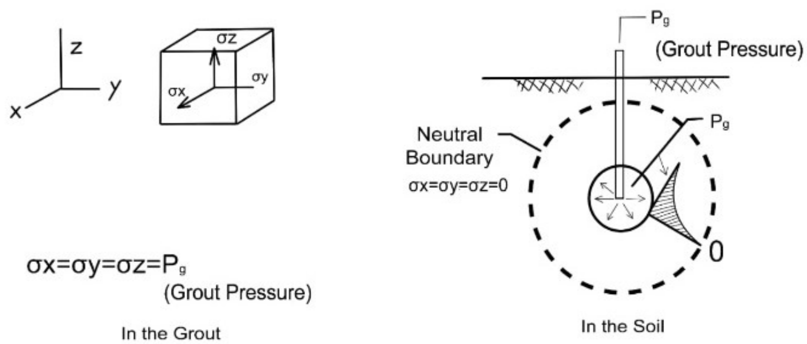

Figure 3. Ground stress conditions around the injection point (Al-Alusi, 1997)

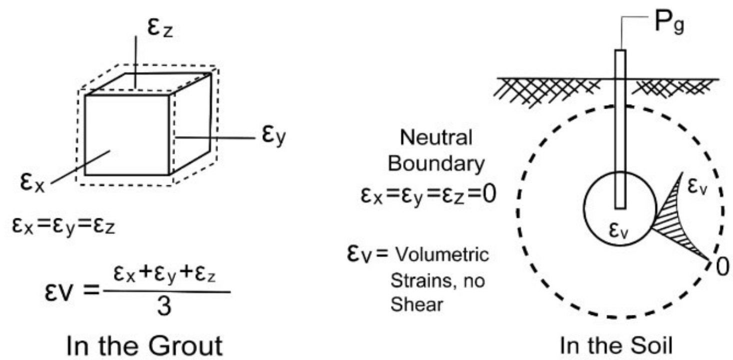

Figure 4. Ground strain conditions around the injection point (Al-Alusi, 1997)

For homogeneous, linear, elastic, and isotropic soils, the volumetric strain is the volume of grout divided by the volume of soil within the neutral boundary, or it can be expressed in the following equation.

$$\varepsilon_v = \frac{V_g}{V_{nb}} \tag{1}$$

where ε_v is the soil volume strain, V_g is the volume of grout, V_{nb} is the volume of soil within the neutral boundary.

The bulk soil modulus, E_b, can be expressed in term of grout pressure and volumetric strain:

$$E_b = \frac{P_g}{\varepsilon_v} \tag{2}$$

$$\varepsilon_v = \frac{P_g}{E_b} \tag{3}$$

then by substituting equation 1 into equation 3, the expression becomes:

$$\frac{V_g}{V_{nb}} = \frac{P_g}{E_b} \tag{4}$$

$$V_g = \frac{P_g V_{nb}}{E_b} \tag{5}$$

Further, the bulk density increase of the soil is expressed as:

$$\Delta\gamma = \frac{\Delta m}{V_{nb}} \tag{6}$$

where Δm is the additional weight added to the sphere. The extra weight added, which increases the soil bulk density in the sphere, is the volume of grout multiplied by the unit weight of soil in the sphere.

$$\Delta m = \gamma_s V_g \tag{7}$$

where γ_s is the unit weight of the soil at the injection point. Then, the additional bulk density increase can be expressed as:

$$\Delta\gamma = \frac{\gamma_s P_g}{E_b} \tag{8}$$

For liquefiable soils in fully saturated state (Sr = 1), the density increase of soil due to grouting is from dissipation of pore-water. The volume of water dissipated is equal to the volume of grout injected. Figure 5 illustrates the mechanism.

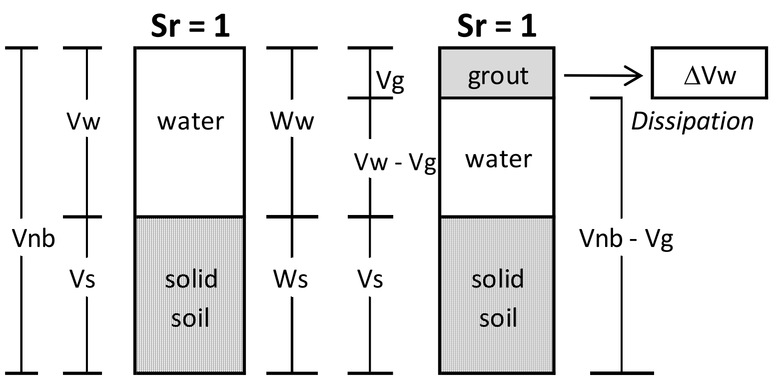

Figure 5. Soil condition before and after grouting injection

Different to the Al-Alusi model, instead of using bulk density, the grouting model developed in this paper uses dry density. The initial dry density of the soil can be expressed as:

$$\gamma_d = \frac{W_s}{V_{nb}} \tag{9}$$

In the presence of hardened grout in the grouted soil mass, the volume of neutral boundary, V_{nb} is reduced by V_g and the soil dry density becomes:

$$\gamma_d' = \frac{W_s}{V_{nb} - V_g} \quad , \gamma_d' > \gamma_d \tag{10}$$

Grout Content, *GC* is defined as the ratio between the volume of grout and the volume of grouted soil:

$$GC = \frac{V_g}{V_{nb}} \tag{11}$$

$$\gamma_d' = \frac{\gamma_d}{1-GC} \tag{12}$$

$$\Delta\gamma_d = \gamma_d' - \gamma_d \tag{13}$$

$$\Delta\gamma_d = \frac{\gamma_d}{1-GC} - \gamma_d \tag{14}$$

Grouting efficiency, η is:

$$\eta = \frac{\gamma_d'}{\gamma_d} \tag{15}$$

$$\eta = \frac{1}{1-GC} \tag{16}$$

where GC is the grout content, V_g is the volume of hardened grout, V_{nb} is the volume of soil in the neutral boundary, γ_d is the dry density of the soil before grouting, γ_d' is the dry density of the soil after grouting, and W_s is the weight of soil grains.

Again, for homogeneous, linear elastic, and isotropic soils, the volumetric strain is the volume of grout divided by the volume of soil within the neutral boundary, or it can be expressed in the following equivalence:

$$\varepsilon_v = \frac{V_g}{V_{nb}} \tag{17}$$

$$E_b = \frac{P_g}{\varepsilon_v} \tag{18}$$

$$\varepsilon_v = \frac{P_g}{E_b} \tag{19}$$

then the substitution of the two above equations becomes:

$$\frac{V_g}{V_{nb}} = \frac{P_g}{E_b} \tag{20}$$

$$P_g = \frac{V_g}{V_{nb}} \times E_b \tag{21}$$

then the substitution of equations (11) with (21) yields:

$$P_g = GC \times E_b \tag{22}$$

The grouting pressure is proportional to the grout content and the bulk modulus. The magnitude of the bulk modulus, E_b, can be estimated by using constraint modulus or oedometer modulus, M, which can be obtained from one-dimensional consolidation testing.

$$E_b = \frac{M(1+\upsilon)}{3(1-\upsilon)} \tag{23}$$

4 MODEL VERIFICATION IN THE LABORATORY

To verify the hypothesis used in the development of grouting model shown in Figure 5, grouting experiments were carried out in the laboratory with schematic diagram shown in Figure 6. Liquefiable fine sand is placed in a transparent cylindrical tube made of Plexiglass. Photograph of the experimental setup can be seen in Figure 7.

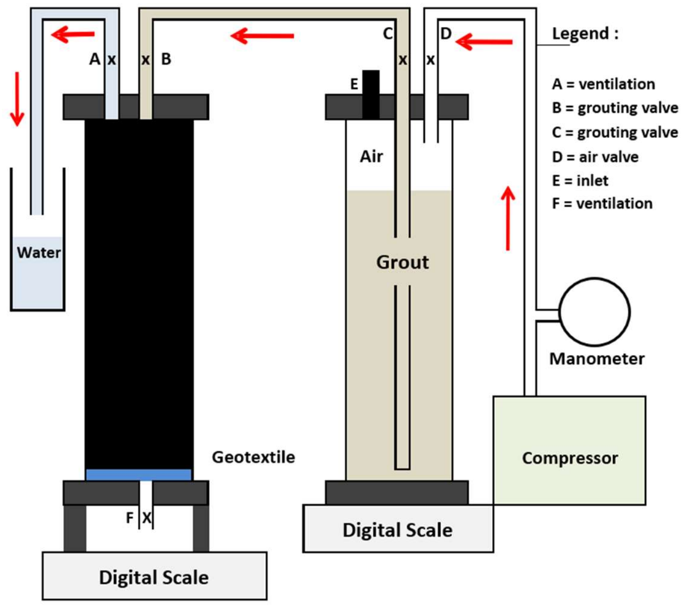

Figure 6. Schematic diagram of grouting experiment at the laboratory

Figure 7 Photograph of the grouting experiment

The experiment began by placing dry fine sand sample in the Plexiglass cylinder with designated dry density. Then the sample is saturated by free-flowing water through ventilation tap F. The saturation process was carried out as slow as possible, to minimize disturbance to the sample grain structure. After the completion of the saturation process, the sample is allowed to stand for 24 hours.

The grout was made of ordinary Portland composite cement (PCC) with water cement ratio, W/C = 3, and to reduce bleeding, additional 3% bentonite powder was added. After homogeneously mixed, the grout is injected by using air pressure from the compressor. The grout flows through the plastic hose (grouting valve) and then into the fine sand. The injection pressure can be read on the manometer and adjusted through a regulator. The volume of grout flowing is monitored through changes in the weight of the grout cylinder and the soil sample cylinder (both cylinders were placed on digital scales). During the injection process, the grout will push water out through tap A. The water expelled is measured in a measuring cup which sit on the scale. Thus, the injected grout that enters the fine sand cylinder and the water that is expelled from the sample can be measured by weight and by volume.

Table 1. Results of trial grouting on saturated loose fine sand in the laboratory

No.	Description	Unit	Test #1	Test #2	Test #3
1	Grouting Pressure	kPa	50	100	200
2	Injection Duration	sec	60	60	60
3	Injected Grout	cm^3	1259	1530	1845
4	Dissipated Water	cm^3	1200	1490	1798
5	Dissipation Time	Min.	1.613	2.468	5.040

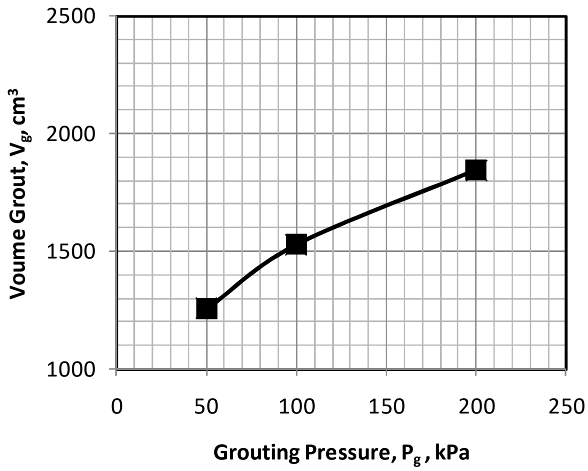

Figure 8. Relationship between grouting pressure, *Pg* and grouting volume, *Vg*

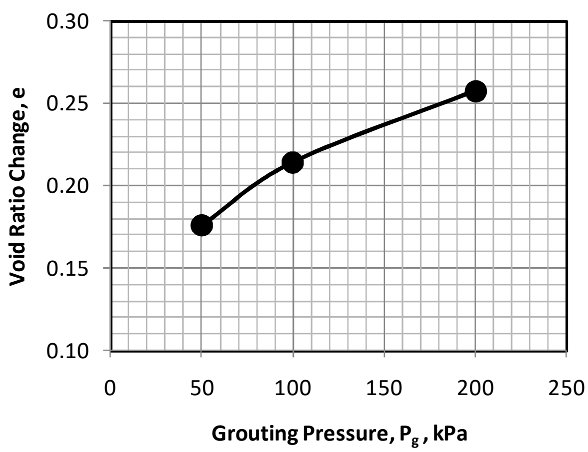

Figure 9. Relationship between grouting pressure, *Pg* and void ratio change, Δ*e*

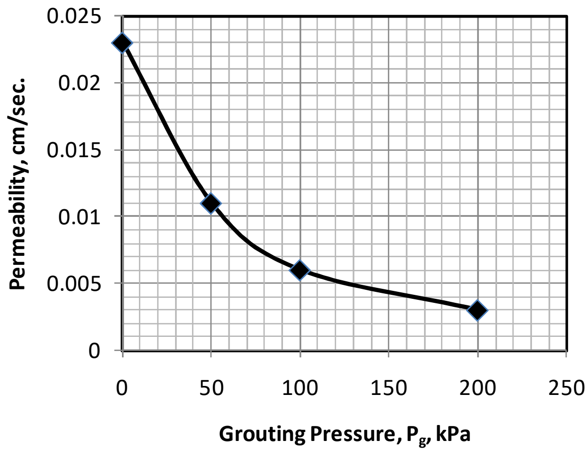

Figure 10. Relationship between grouting pressure, *Pg* and permeability, *k*

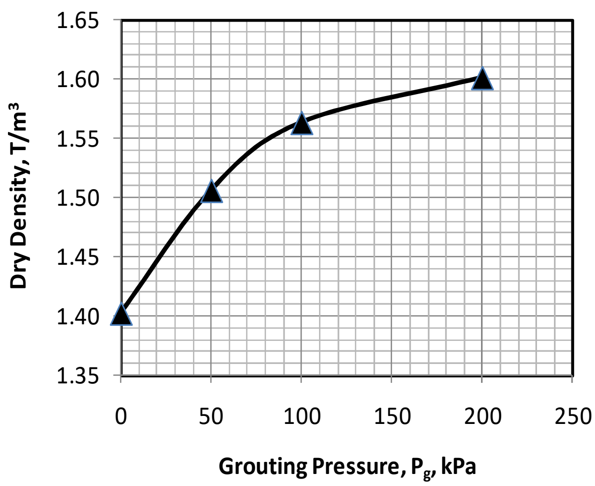

Figure 11. Relationship between grouting pressure, P_g and dry density, γ_d

5 CONCLUSION

Based on experiment in laboratory on the application of grouting for the improvement of loose fine sand which has the liquefaction potential, the following conclusions are made:

- As the grouting process commenced the grout liquid instantaneously displaced pore water in the sample. The amount of water dissipated is equal to the amount of grout injected
- As the grouting pressure increase, the volume of grout increase
- As the grouting pressure increase, the void ratio changes, or reduction increase
- As the grouting pressure increase, the permeability is decreased
- As the grouting pressure increase, the dry density increase. The dry density was reaching an asymptote
- As the sample becomes denser due to the previous injection, a higher pressure is needed to inject the grout into the sample. It proves that the injection pressure of Pg has relation with the consistency/bulk modulus of the soil and Grout Content, GC, Pg = GC x Eb.
- Soil improvement by grouting method applied to liquefiable soil basically improves the soil by mechanical effort, reducing void ratio and increasing soil dry density followed by shear strength increase.
- The grouting material used does not have to be PCC cement, for example fly-ash or silt which is not plastic can also be used.

DISCLAIMER

The author has no competing interests to declare that are relevant to the content of this article.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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