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COMPACTION GROUTING: FROM PRACTICE TO THEORY

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Abstract

Compaction grouting is a method of in-situ soil densification by grout injection under pressure. With almost no theoretical consideration, compaction grouting emerged from "mudjacking" applications, through deep slurry consolidation to evolve into a compaction idea that was perpetually perfected using available theory to reach today's state-of-the-art technology.

This paper presents the requirements for successfully implementing a compaction grout densification program (CGD Program). It presents what the geotechnical engineer should look for during the investigation campaign and how to develop findings into design parameters. Mathematical and physical models of the CGD method are reviewed. Improvement in bearing capacity, reduction of settlements, or density considerations are given with applications. Further research ideas and directions are discussed.

Introduction

Conceptually, compaction grout is injected under pressure to displace the soils and produce higher in-situ density. With today's state-of-the-art technology, compaction grouting requires a minimum of three main components: suitable knowledge of site soils, proper equipment, and the know-how to apply the technique to achieve the target results.

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Although knowledge of the site soils and proper equipment are essential for a compaction grout densification program (CGD), this article will not be dealing with these items specifically. This article's main focus will be on the understanding and the successful application of a CGD program.

Mudjacking (slabjacking) has been known to involve the use of cement slurry or "mud", which is a mixture of sand and cement. Because of its high mobility, once the slurry grout fractured the soil, it was impossible to control its installations. Sanded mixes offered better control depending upon their sand content and viscosity. However, the use of sanded mixes (mud) was not without problems.

In the 1940's and 1950's, equipment was not available that could deliver sanded grout at high pressures. Although the grout pressure did not need to be higher than a fraction of a N/mm^2 to allow for the weight of the slab, along with whatever local resistance existed, the technology at that time lacked two main aspects; namely, availability of equipment and an understanding of the behavior of the grout being used.

As equipment improved, providing better delivery, higher pressures, and more accurate monitoring, it was realized that for a heavy slab with additional local resistance, the grout was pressing and densifying the underlying soil before lifting the slab to the required level. The next step was to extend the pipe into the soil to obtain better densification, then extend the pipe to a lower depth to densify the lower soils. This became known as top-to-bottom (stage-down) compaction.

The relationship between grout viscosity and soil consistency was not clear enough to secure controlling the placement of grout without fracturing the soil and losing control over it. It took some time and exposure to understand this relationship.

Before the geotechnical engineer's involvement, this approach was hit-or-miss, depending upon what depth the operator could reach, how much effort was available, and what pressures the equipment could deliver. The geotechnical engineers, inside and outside the specialty contracting field, provided the necessary soil information and the anticipated objectives of the grouting program.

However, in stage-down compaction, it is tedious to densify an upper zone, then drill through the compacted grout, reinstall the injection pipe, and then reseal it. From a practical point of view, this procedure is not efficient. Though it could be argued that the added grout helps by introducing additional weight to the soil for improved confinement, in reality an added weight of only five to ten percent has a negligible effect on the densification process. It was quickly realized that whatever, if any, benefits were derived from this procedure, they were outweighed by the cumbersome impracticality.

Stage-up compaction (bottom-to-top) is a more efficient technique. In this process, a grout pipe is installed to the maximum depth required (usually a competent soil/rock layer) and compaction starts on top of it, proceeding upwards in increments of about 60 centimeters or less. In terms of drilling and pipe installation, a stage-up process is superior and does not involve resealing, redrilling, or reinstallation of the injection pipe. As a result, stage-up compaction is typically employed as more efficient and cost- effective.

Relationship Between Soil Type, Grout Viscosity, Pressure, and Required Volume of Grout

With time and extensive practical use of "compaction grouts", it became clear that the viscosity of the injected grout must be limited. In 1980, the Committee on Grouting of the Geotechnical Engineering Division of ASCE defined compaction grout as not more than one-inch (25mm) slump. Slump value is per ASTM C143. Although this requirement can be used for the majority of encountered soils, it is too restrictive for low consistency soils, such as peat, very soft clays and silty clays. On the other hand, it is not conservative for high friction soils such as sands/ silty sands, where a slump of less than 25mm is needed. Figure 1.a represents the qualitative relationship between the type of soil and the required slump value.

Grout pressures are related in an opposite way to the soil type from grout viscosity. Figure 1.b shows pressure requirements for various soils. The rate of pumping is high for low consistency soils and low to very low for high friction soils, see Fig. 1.c.

Because of their ease in accepting grout under pseudo-static conditions, low friction soils accept more grout volumes than high friction soils, as qualitatively shown in Fig. 1.d. This results in higher degrees of improvement for soil density, as depicted in Fig. 1.e.

Each of the figures (Figures 1.a through 1.e) are for one variable versus the type of soil, assuming all other variables and equipment capabilities are the same.

Theoretical Considerations

For a homogeneous, isotropic material, the grout pressures within the soil mass dissipate at a spherical boundary, centered at the tip of the injection pipe. At this boundary stresses and strains caused by the grouting process are nil. For the purposes of this discussion, call this boundary the neutral boundary. The following state of stress shall exist:

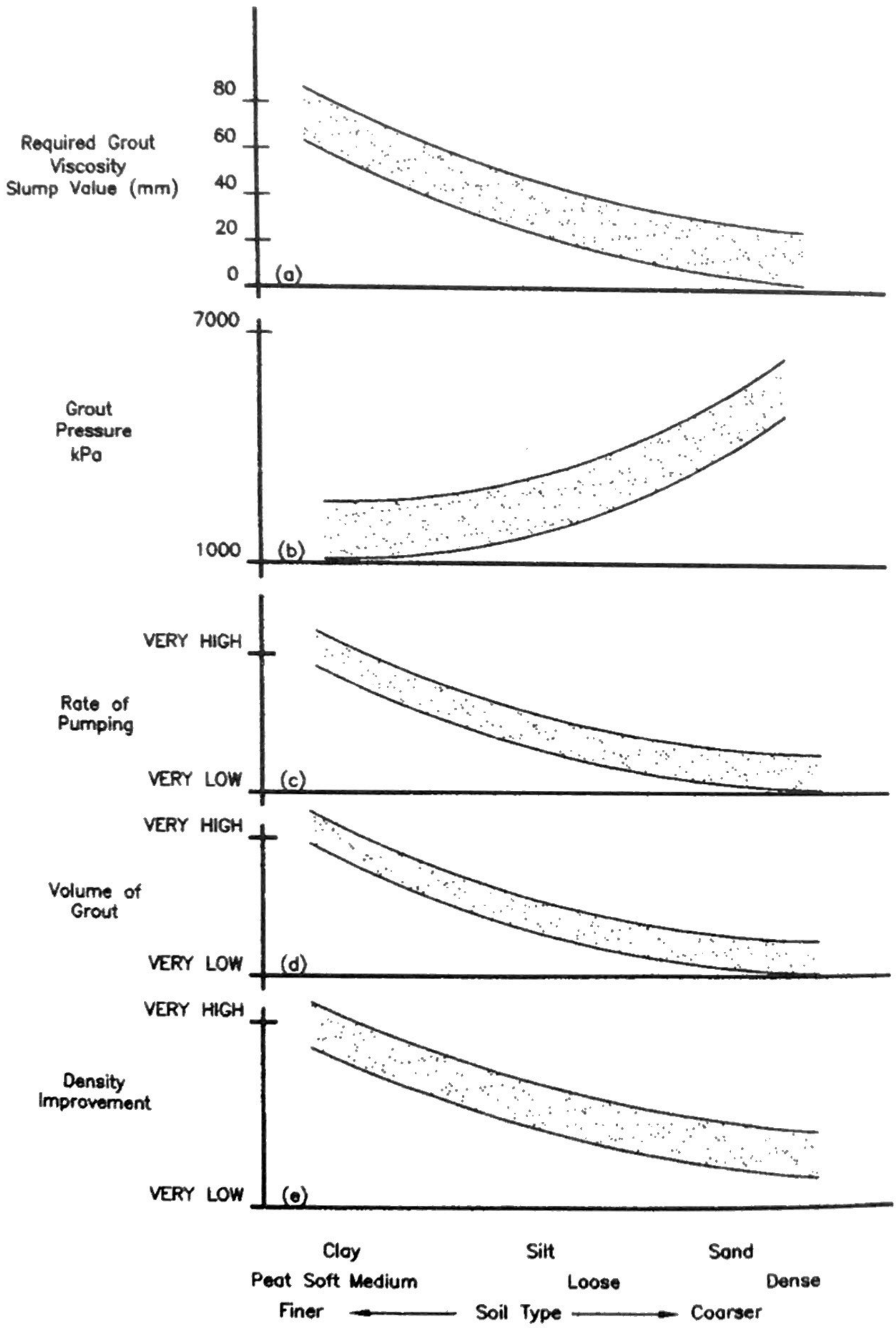
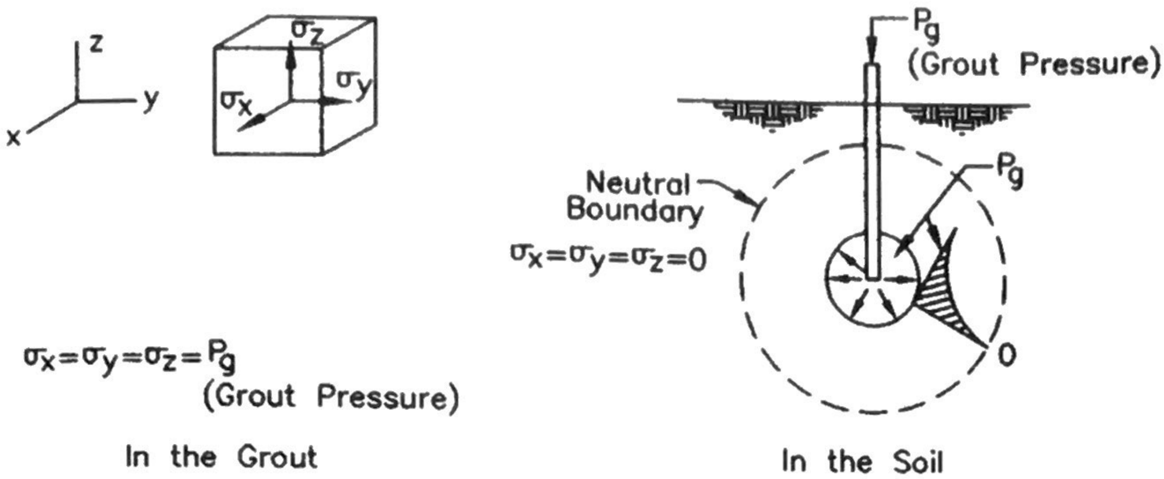
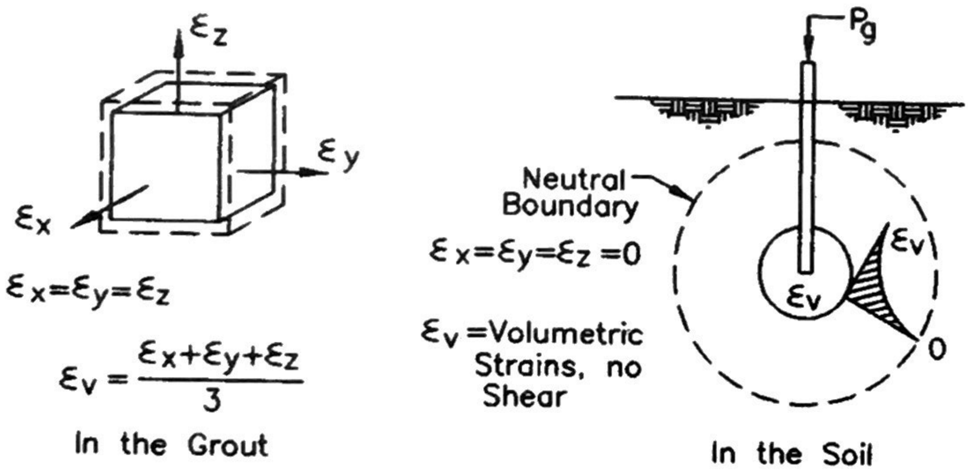


Figure 1. Relationship Between Grout Parameters and Soil Type



The strains within the soil mass can be represented by:



For a homogeneous, linear, elastic, and isotropic material, volumetric strain is the volume of grout divided by the soil volume within the neutral boundary, or:

$$\varepsilon_v = \frac{V_g}{V_{nb}} \qquad \text{[1]}$$

where: V_g = volume of grout
V_{nb} = volume of soil within the neutral boundary

If we define a soil bulk modulus as $E_b = \dfrac{P_g}{\varepsilon_v}$

or,

$$\varepsilon_v = \frac{P_g}{E_b} \qquad \text{[2]}$$

substituting equation [1] into equation [2], gives

$$\frac{V_g}{V_{nb}} = \frac{P_g}{E_b} \qquad \text{[3]}$$

The increase in density of the soil mass (Δ_γ) can be represented as:

$$\Delta_\gamma = \frac{\Delta_m}{V_{nb}}$$ where Δ_m is the "introduced mass",

substituting for V_{nb} from equation [3], gives

$$\Delta_\gamma = \frac{\Delta_m}{V_g} \cdot \frac{P_g}{E_b}$$

The "introduced mass" is not the mass of the injected grout. The mass introduced into volume V_{nb} which effectively raises the density of the soil within V_{nb} is the volume of the introduced grout multiplied by the density of the soil itself. To better understand the effect of this mass, let us assume that the grout is injected in a balloon and that air is used instead of grout. What the air and balloon would displace is a mass with volume of grout V_g and a density of soil γ_s. On the other hand, if we assume that we inject a grout of an extremely high density, such as ($\gamma_g = \infty$), then the same argument holds, i.e., the effect of introducing such a grout on the soil mass surrounding it is also equal to the volume of the injected grout times the density of the soil itself. Hence, the effect of the grout density is irrelevant, and

$$\Delta_m = V_g \cdot \gamma_s$$

where: γ_s = unit weight of the soil at the point of injection

therefore,

$$\Delta_\gamma = \gamma_s \cdot \frac{P_g}{E_b}$$ or

$$E_b = \gamma_s \cdot \frac{P_g}{\Delta_\gamma} \quad \text{...[4]}$$

For a given site, γ_s can be taken as a constant for all practical purposes. E_b, by definition, represents the relationship between the volume and the pressure of the grout. E_b is a property of the soil.

Collected pressures and improvements of the soil density by the author are presented in Table 1. The soils bulk modulus is determined according to equation [4]. Plotting these values against soil type gives us Fig. 2, which is in qualitative agreement with Fig. 1.b.

Soil may be, to a practical degree, homogeneous enough to allow same properties from one point to another within a soil mass. Thick soil formations are expected to exhibit more isotropical behavior than thin zones and layers. Most soils, specifically man-made fills and residual soils, tend to be orthotropic rather than isotropic. Again, soil deposits of relatively high thicknesses are expected to have some degree of isotropy.

Linearity and elasticity are the least two assumptions that can be satisfied by everyday soils. At low strain levels, soils may exhibit certain linearity and elasticity aspects. However, at higher strain levels soils are neither linear nor elastic.

Practical Considerations

Grout introduced in the ground forms a bulb (Al-Alusi, 1994 & 1996) without permeating the soil or fracturing it. The formation of such a bulb is directly connected to the equipment's capabilities to deliver the proper viscosity grout and at sufficient pressures. In order to pump a 25-50mm slump grout at a pressure of 3000-7000 kPa, it takes specialized pumps and proper material. Grout is introduced into the soil mass, displacing air, solids, and water. In this regard, two main categories of soils need to be recognized: an unsaturated soil and a saturated soil.

In an unsaturated soil, there is no need to impose a limit on the rate of grout pumping, while in a saturated soil it is limited by the ability of the soil mass to dissipate the generated pore water pressure. Otherwise, the pore water pressure dissipation can be expedited by way of wick drains, sand drains, or perforated stand pipes. Other considerations are:

1. Thickness of the grouting zone:
   The grouting procedure should be applied to the full thickness of a soft/loose soil layer when undertaking the eradication of settlements. Improving only a portion of the settlement contributing zone may aggravate the problem. The whole zone should be densified unless a detailed settlement calculation including the added mass of grout, shows that future settlements are acceptable.

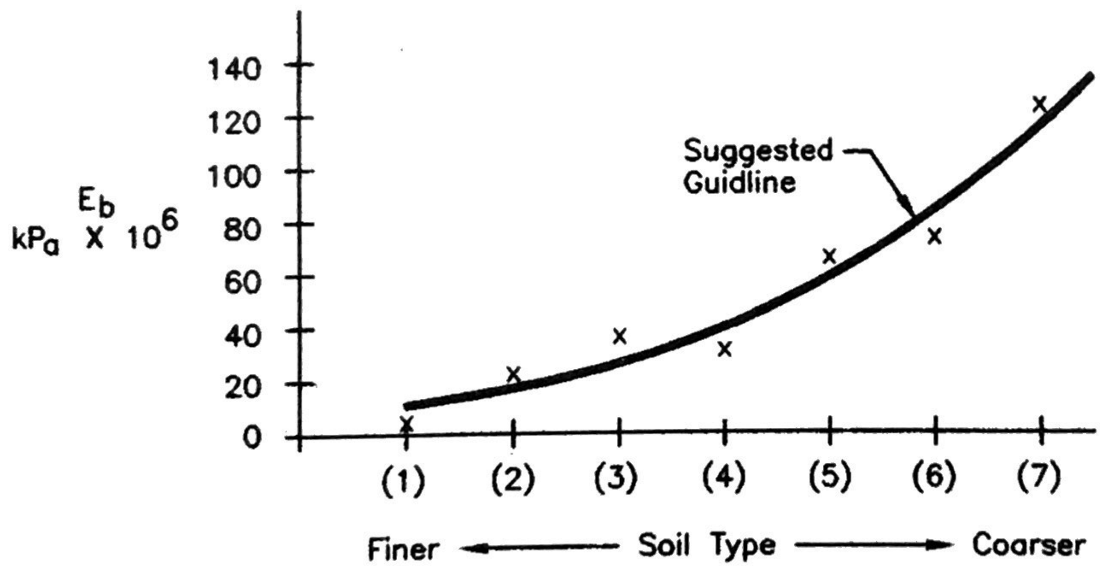


Figure 2. Relationship Between Soil Bulk Modulus (E_b) and Soil Type

When there is a bearing capacity insufficiency for a concentrated load, compaction can be carried out to improve the soils in the vicinity below the foundation element without necessarily reaching a competent soil layer. However, such a load transfer does not necessarily eliminate a settlement problem.

2. Spacing of Injection Points:
   A primary, secondary, tertiary system should always be used as much as possible. An equilateral triangular spacing is the most efficient for a grid pattern. Common primary spacing is 2.5, 3.0 or 3.7 meters depending on the thickness of the layer that needs to be densified. Further space splitting is possible by introducing injections within the triangles.

3. Staging:
   For best results, vertical staging should be reduced to the shortest practical distance. A 60-cm (two-foot) staging is usually used with a tendency to limit it to 30-cm only (one-foot).

4. Sequencing:
   Sequencing is a tool to confine the effects of grout and limit it to a pre-defined area. In a large open area that needs to be densified, compaction injections should be placed around the whole area (i.e., around the perimeter). The interior of this area is then densified. One way this can be accomplished is by isolating the overall area into suitable cells, then densifying the perimeter of each cell, followed by densification of the interiors.

5. Effects of soil stratification:
   For soil profiles where a relative soft/loose (low E_b) layer is next to a firmer (high E_b) layer, the possibility of grout puncturing through the high E_b layer to the low E_b layer exists. For such a condition, the lower E_b layer should be densified first to a point where its density matches the high E_b layer.

6. Effects of a CGD program on groundwater movement:
   The introduction of discrete bulbs of grout together with the densification effect around them, have a negligible influence on the permeability of silts, clays and their combinations. Theoretically, in sands, silty sands and their combinations, an effect exists, although such effects are hardly measurable. First, unlike piles or large diameter shafts, compaction grout bulbs are discrete, and second, the target of the CGD Program is to raise the soil density by a small percentage (5% to 15%), which in turn produces practically immeasurable permeability changes in subsoils.

7. Stoppage Criteria:
   a. Grouting performance, such as the amount of predetermined grout consumed (grout take), maximum pressure reached, or a given rate of pumping at a given pressure.

b. Grouting procedure failure, such as a sudden drop in pressure, indicating soil fracture (10 kPa or more).
c. Grouting site limitations, such as the maximum grout pressure that can be reached, pressure within the soil as measured by a pressure cell embedded in the soil, or vertical or lateral movement of an inclinometer, pile top, retaining wall, footing, etc.

8. Effects of Grout Strength:
The strength of grout material has absolutely no effect on compaction performance whatsoever. Grout bulbs are discrete without interconnections. Therefore, the strength of the grout material is irrelevant. This relates very well to the same finding of irrelevance for the density of the grout material as presented above.

Future Research and Directions

The relationship between grout viscosity and soil consistency is probably of prime importance for the successful achievement of a CGD Program. Fig. 1.a will need to be quantified through fully controlled CGD Programs, followed by verifications. At present, practitioners tend to be conservative by lowering the required slump value.

The amount of grout needed to raise a soil's density to a prescribed value, such as the relationship given in Fig. l.e, will need to be verified assuming the soil mass to be homogeneous after a CGD Program.

Values for the volume of grout will follow almost directly into Fig. 1.d and hence will quantify both Figs. 1.d and 1.e.

A factor that can help tremendously in establishing Figures 1.b, 1.c, 1.d and 1.e is E_b. Although Table 1 is based on actual grouting case histories, E_b values and relationships to other established soil parameters can be improved using existing engineering data.

Conclusions

Soil improvement by in-situ densification using pseudo-static compaction techniques have been successfully used with limited theoretical understanding. Although not much theoretical understanding has been behind the development of the CGD systems, such an understanding is prerequisite to solidifying and crystallizing the main concepts of the technique.

Another integral part of this understanding is the information derived from controlled performance data and subsequent verifications. The need is still high for results of controlled densification projects. The density of the grout material itself is found to be irrelevant to the performance of the technique. A new term, Bulk Modulus of Soil, is introduced which relates the pressure of grout to the volume of grout, and hence the degree of soil improvement. The irrelevance of both the strength and density of the compaction grout is proven.

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Table 1

Guideline Values of Bulk Modulus
For Different Soil Types

Soil Type	Soil Density Kg/m^3	Grout Pressure kPa	Increase in Density %	Modulus E_b, kPa X 10^6
(1) Peat	970	1500	0.30	4.8
Clay/Silty Clay				
(2) Soft	1300	2000	0.20	19.5
(3) Medium	1450	3500	0.15	33.8
Sandy Silts/Clay				
(4) Soft	1300	3500	0.15	30.3
(5) Medium	1450	4100	0.10	59.5
Silty Sands/Sands				
(6) Loose	1300	4100	0.08	66.6
(7) Medium	1600	5500	0.07	125.7