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Laboratory investigation into effectiveness of thixotropic gel compaction method

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ABSTRACT: In the Thixotropic Gel Compaction (TGC) method a grout material that is basically a fly-ash mortar is injected into the soil. During injection, this grout material increases in size and displaces the surrounding soil without mixing with or penetration into the soil. This mechanism of grout expansion renders the method effective in improving the in-situ loose soils and in compensating the ground settlement associated with underground excavation and bored tunneling. In this paper, the method is examined through physical modeling in the laboratory using a large-scale double-wall calibration chamber. The calibration chamber and testing procedure are described herein. Also typical results of injection into sandy soil are presented and discussed to illustrate the grouting performance and the variation of soil improvement and compensation effectiveness with injection. The presented discussions reveal significant observations that can be used to effectively plan the TGC grouting works.

1 INTRODUCTION

In the Thixotropic Gel Compaction (TGC) method a grout material that is basically a fly-ash mortar is injected into the soil. The composition and characteristics of the TGC grout are described by Shimada et al. (2005). During injection, the grout material increases in size and remains in a homogeneous state resulting in displacement of the surrounding soil through a distinct grout-soil interface.

The mechanism of treatment by displacement provides for controlled treatment, as the required amount of grout can be injected where needed. This has the advantage of the possibility of varying the grout volume to account for the variation of soil properties, so that given target or uniform results can be obtained. The method is applicable to all soils that are compactable. Therefore, it can be used as a ground improvement technique to increase the bearing capacity or to minimize the liquefaction potential of the in-situ loose soils. The treatment mechanism renders the method also capable of inducing upheave of the soil, and as a result can be used to compensate the ground settlement associated with underground excavation or bored tunneling.

The grout material can be injected into the soil through injection pipes to form discrete grout bulbs or grout piles. An economically feasible procedure is to inject the grout material in stages while going upward. In such a procedure, after drilling to the bottom boundary of treatment zone, the lowermost bulb is injected. Then, the pipe is pulled upward for a given depth interval and the next bulb is injected. This procedure is followed till reaching the upper boundary of treatment zone. An alternative procedure is to inject the grout material through a sleeved tube known as a *tube à manchette* (TAM). The TAM is a plastic or steel pipe with pairs of holes drilled at intervals along the length of the pipe. Such holes are covered by tight rubber sleeves that act as non-return valves. The use of TAM provides more flexibility in performing the grouting works, where the grout material can be injected at any pre-determined order in both of the vertical and lateral directions throughout the treatment zone. Such a control of the injection sequence is useful where the injections can be planned, so that the previous injections provide confining actions for the subsequent ones in both of the vertical and lateral directions. The use of TAM along with the TGC grout that is thixotropic has an additional advantage of allowing re-injection of grout from the same port, if needed. The use of the appropriate procedure depends on the site conditions and economic considerations.

In this paper, the effectiveness of the TGC method is examined for both of the ground improvement and settlement compensation works. For this purpose, the method has been physically modeled in the laboratory using a large-scale calibration chamber.

This chamber is of the flexible double-wall type and has been developed to allow for preparing, consolidating and injecting soil samples under conditions approximating the actual in-situ ones. The paper starts with a brief description of the calibration chamber and the testing procedure. Then, typical results of injection into sandy soil are presented. These results are further discussed to illustrate the grouting performance in terms of the corresponding soil stresses and deformations and the variation of soil improvement and compensation effectiveness with injection.

2 EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the setup of the calibration chamber and the setting of injection pipe. The chamber is of the flexible double-wall type that well simulates the in-situ conditions (Holden 1971) and consists of seven major components: chamber base, loading piston, side membrane, double-wall barrel, retaining cylinder, lid and assembly rods. The chamber details, testing procedure and differences with the other double-wall chambers in use, as well as the required corrections for the effects of chamber size and boundary conditions, are reported by El-Kelesh and Matsui (2006). The principal features of the chamber are summarized in the following (see Fig. 1):

- The sample, 1.40 m in diameter and 1.45 m in height, is enclosed inside a cylindrical rubber membrane.
- The vertical stress is applied at the top of sample via the piston by pressurized air, while the lateral stress is applied by water filling the annular space between the side membrane and barrel.
- It utilizes a double-wall barrel to control the K_0-condition and impose different boundary conditions. The annular space between sample and inner wall (inner cell) as well as that between the inner and outer walls (outer cell) are filled with de-aired water. On increasing the vertical stress, the pressure of inner cell increases due to the tendency of sample to deform laterally. An electro-pneumatic (E/P) regulator is used to control the pressure of outer cell and keep it equal to the developed pressure of inner cell. This control assures no deflection of the inner wall, and therefore an average zero lateral deformation of the sample.
- It provides for upheave of the sample surface and can independently control the sample vertical stresses and lateral stresses and strains.
- To simulate the free-field conditions, the required boundary conditions of the sample are expected to be between the limits of constant stress and zero average strain on both the vertical and horizontal boundaries. The chamber panel of controls can impose these boundary conditions.

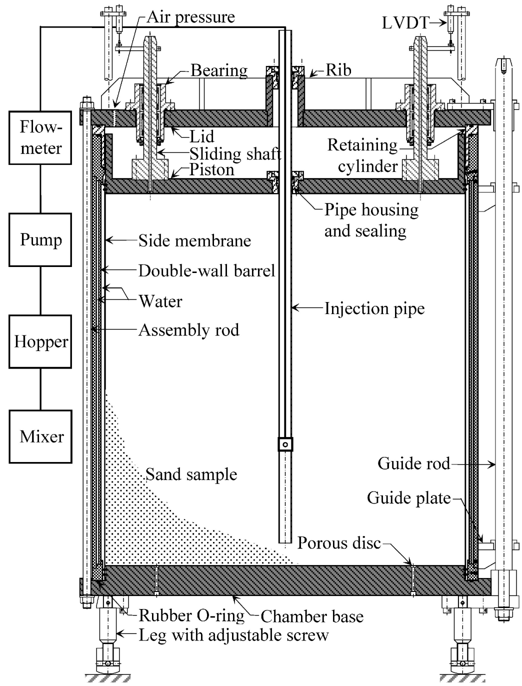

Figure 1. Setup of calibration chamber and injection system and positioning of injection pipe.

- It utilizes a carefully designed vertical sliding system consisting of four shafts fixed to the piston and slide through linear bearings bolted to the lid. This system provides for sample vertical compression of 125 mm and upheave of 25 mm from the initially prepared sample surface. It also allows for externally measuring the displacement of sample surface through the four sliding shafts and four Linear Variable Displacement Transducers (LVDTs) attached to the lid.
- The piston slides through a rubber O-ring recessed in an annular shoulder machined in the inside of the barrel.

The injection system consists of mixer, hopper, squeeze pump, flow meter and double packer. The flow meter is used to measure the injected volume of grout. The injection pipe passes through central holes in the lid and piston. It is perforated at 1.0 m from the sample surface. The pipe perforations are covered with a cylindrical rubber sleeve that acts as a non-return valve for the grout material.

The test is conducted in five stages: sample preparation, chamber assembly, sample consolidation, injection and chamber disassembly. A funnel system consisting of hopper, flexible tube and rigid PVC pipe is used for sample preparation. The flexible tube connects the hopper to the PVC pipe. The hopper filled

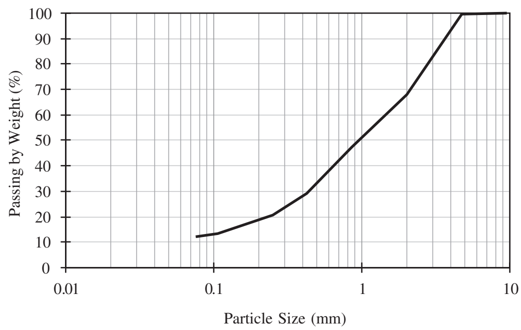

Figure 2. Gradation of test sand.

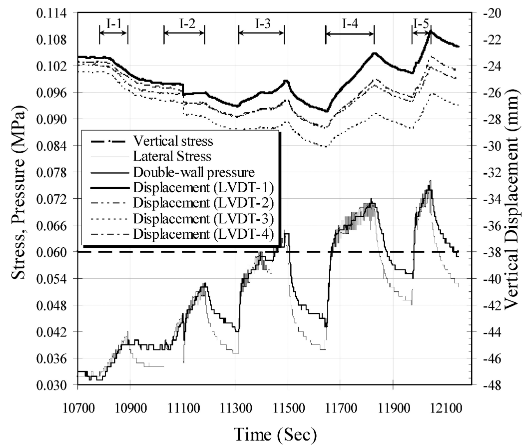

Figure 3. Vertical and lateral stresses and vertical displacement of soil during injection and suspension.

with sand is hung by an overhead crane and the sand is dispensed by opening the hopper outlet valve. The sand is deposited inside the rubber membrane (that is stretched inside a split sample former), after positioning the injection pipe guided by a centralizing bar, in horizontal thin layers by horizontally moving the PVC pipe forward and backward in parallel lines. The density is controlled by varying the falling height of sand that is the distance between the lower end of the PVC pipe and the surface of deposited sand. After filling the split former, the sand surface is leveled, the piston is gently lowered on the top of sand and the side membrane is sealed against the piston by means of metallic O-rings. Then, vacuum is applied to the sample and the split former is disconnected leaving a vacuum-stabilized sample. The chamber is then assembled around the sample, connected to the panel of controls and filled with de-aired water. After releasing the vacuum, the sample is consolidated under the K_0-condition by increasing the vertical stress in increments till reaching the consolidation stress. Then, the double packer is lowered into the injection pipe and inflated, the pump is set to the desired injection rate and injection is proceeded. After hardening of the injected grout material, vacuum is applied to the sample, the panel of controls is disconnected, the water is emptied and the chamber is disassembled.

The test soil is an air-dried natural sand, the gradation of which is shown in Figure 2. The specific gravity, maximum void ratio and minimum void ratio of the test sand are 2.650, 0.923 and 0.562, respectively. The sand was deposited at a relative density of 50% and consolidated by increasing the vertical stress in increments until reaching a consolidation stress of 0.06 MPa. The injection process was volume controlled and performed under the boundary condition of constant vertical stress and zero average lateral strain (BC3). A grout material of 46 L in volume was injected in five stages (I-1 to I-5); about 10 L/stage for I-1 to I-4 and 6 L for I-5. The injection pump was set to an injection rate of 5 L/min. and a time lag of 2–3 min. between every successive injection stage was considered, resulting in five suspensions of injection (S-1 to S-5).

3 GROUTING PERFORMANCE

The grouting performance may be understood by examining the variation of soil stresses and deformations with injection. Figure 3 shows the soil vertical and lateral stresses, the double-wall (outer cell) pressure and the vertical displacement of soil surface (as measured by the four LVDTs) measured during the injection and suspension stages. The initial values shown in the figure are those attained at the end of consolidation and before starting the injection. It is seen that the E/P regulator was satisfactorily responding to the changes in the lateral stress. The lateral stress and vertical displacement are re-plotted in Fig. 4 to show their variation with the injected grout volume (as measured by the flow meter). The vertical displacement in Fig. 4 represents the average of the four displacements shown in Fig. 3.

The results in Figs. 3 and 4 reveal that, as a result of the expanding grout, the soil experienced gradually increasing lateral stress with injection. However, in terms of the vertical displacement, the soil experienced gradually increasing settlement during I-1, followed by practically no change during I-2, and then continuously increasing upheave during I-3, I-4 and I-5.

During suspension, the soil experienced gradually decreasing lateral stress and increasing settlement with time. The boundary condition BC3 was imposed on the sample during injection and suspension. This along with the fact that the rubber sleeve of the injection pipe acts as a non-return valve indicates that during suspension the soil did not experience a displacement at the

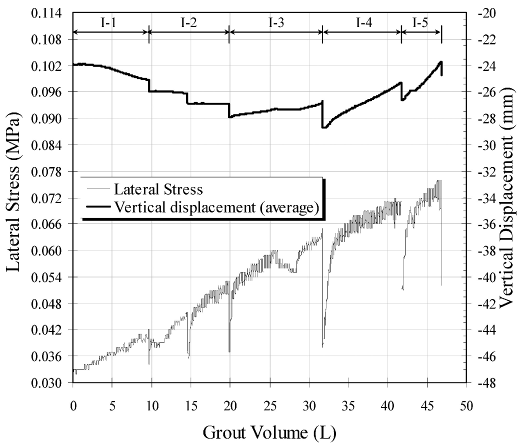

Figure 4. Variation of soil lateral stress and vertical displacement with the injected grout volume.

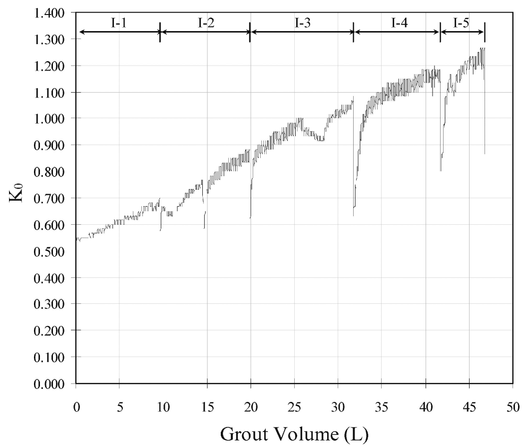

Figure 5. Variation of coefficient of earth pressure at rest (K_0) with injected grout volume.

lateral boundary of the soil or at the gout-soil interface. Nonetheless, it experienced gradually decreasing lateral stress and increasing surface settlement. This implies that immediately after the termination of injection and during the suspension, the soil exhibited both of lateral stress relaxation and creep deformations, as a result of re-arrangement of the soil particles till reaching equilibrium.

By carefully examining the results in Fig. 4, it is seen that immediately after resuming the injection (after a given suspension) the lateral stress increased sharply. Then, with continued injection it followed almost the same rate of increase as that of the previous injection stage. It may therefore be reasonable to conclude that the increase of lateral stress follows a practically linear relationship with the injected volume of grout. The results however reveal that the suspension process has a significant effect on the performance in terms of the vertical displacement. It is seen that the variation of displacement during a given injection stage is significantly different from that during the preceding one. Such a difference is attributed to the creep deformation experienced during the suspension stages. These observations reveal the significance of the soil rheological properties in terms of stress relaxation and creep deformation during suspension and indicate that during post-suspension injection the developed lateral stress is not significantly influenced by the suspension process, while the developed soil deformation is significantly influenced.

4 TREATMENT EFFECTIVENESS FOR GROUND IMPROVEMENT WORKS

The soil improvement due to treatment by the TGC grout may be evaluated in terms of the coefficient of earth pressure at rest (K_0). K_0 is an important parameter and is usually considered as a target criterion in most of the ground improvement problems. It is defined as the ratio of the soil lateral stress to the vertical one at the condition of zero lateral strain. The boundary condition BC3 (constant vertical stress and zero average lateral strain) was imposed during injection and suspension. Therefore, the measured lateral stress may be considered as a direct measure of K_0. Figure 5 shows the variation of K_0 with the injected grout volume. It is seen that K_0 increases continuously with injection and has a practically linear relationship with the injected grout volume.

The soil improvement may also be evaluated by examining the variation with injection of the soil volume change that is the change of volume of voids. The soil volume change may be estimated from the injected volume of grout and the corresponding vertical displacement of sample surface, according to the following expression:

$$\Delta V = V_g + V_d \qquad (1)$$

where ΔV = soil volume change; V_g = injected grout volume; and V_d = cross-sectional area of sample multiplied by the vertical displacement of soil surface (positive for settlement, negative for upheave).

Figure 6 shows the variation of the soil volume change as estimated by Eq. 1 and the net vertical displacement of soil surface (due to injection) with the injected grout volume. It should be mentioned that the volume of grout actually expanding into the soil is not strictly the same as that measured by the flow meter. The grout essentially loses an amount of water during injection. This amount depends on the bleeding characteristics of grout. The grout volume considered in Eq. 1 and represented in Fig. 6 is that measured by the

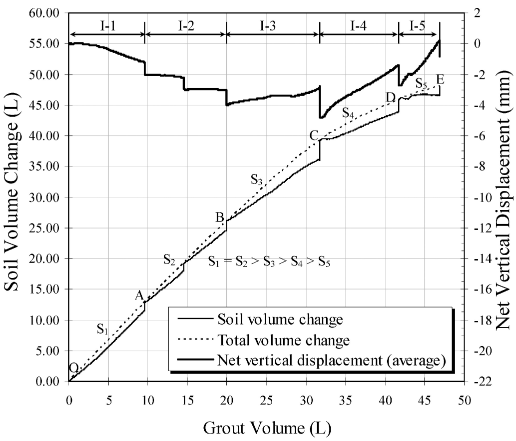

Figure 6. Variation of soil volume change and net vertical displacement with the injected grout volume.

flow meter without being corrected for the water loss. The following observations however can be made (see Fig. 6):

- The volume change increased continuously with injection.
- For a given injection stage, the rate of volume change is practically constant.
- During all the suspension stages, the volume change (compressive) is gradually increasing with time as a result of creep deformation.
- The rate of volume change is decreasing with stage injection. This is explained by the gradual transition of vertical displacement from settlement during I-1 through constant (no change) during I-2 to upheave during I-3, I-4 and I-5.
- It is interesting to note that the onset of upheave (at the beginning of I-3) characterizes two distinct stages of improvement. Before the upheave onset, the lines representing the total volume change due to injection and suspension (OA for I-1 and S-1, AB for I-2 and S-2) have the same slope. However, for the post-upheave onset stages, the slope of the line representing the total volume change (BC for I-3 and S-3, CD for I-4 and S-4, DE for I-5 and S-5) is decreasing with stage injection. The slopes of the lines representing the total volume changes due to the five stages of injection and suspension may be expressed as:

  $$S_1 = S_2 > S_3 > S_4 > S_5$$

  where S_i = slope of line representing the total volume change due to both of I-i and S-i (i = 1, 2, 3, 4 and 5).
- The variation of improvement before and after the occurrence of upheave is explained by the relative contribution of injection to upheave. In other words, it can be said that, before the upheave onset the injection is totally contributing to improvement of the treated soil. However, after the upheave onset, the injection is contributing to both of improvement and upheave. Moreover, the contribution to upheave is increasing with continued injection after the upheave onset.

The above observations on the increase of K_0 and soil volume change with injection are important in planning the TGC grouting for ground improvement works, especially in deciding the grout point spacing and the grout volume to be injected. They imply that the most effective treatment may be attained by planning the grouting works, so that upheave of the soil surface is avoided. However, should larger grout volumes be injected because of economic considerations, the variation of improvement with grout volume should be taken into account.

5 TREATMENT EFFECTIVENESS FOR SETTLEMENT COMPENSATION WORKS

Because of its treatment mechanism (by pure displacement), the TGC method is capable of inducing upheave of the treated soils. This renders the method effective for compensating the ground settlement caused by underground excavation and bored tunneling. The effectiveness of compensation is usually evaluated in terms of the ratio of the upheave volume to the injected grout volume.

Ideally, if injection is made quickly in saturated clayey soil so that soil deformation occurs in undrained condition (incompressible behavior), upheave will occur immediately after the start of injection and its amount will be equal to the volume of injected grout. However, this does not occur in practice, since the volume of grout that expands into the soil is generally smaller than the injected volume (owing to the bleeding of grout water). For sandy soils, in addition to the bleeding of water, the soil does not experience incompressible behavior, but will experience some compression before the occurrence of upheave. With continued injection the attained amount of upheave will be dependent on the soil compressibility characteristics and the corresponding water bleeding. After termination of injection, the upheave attained at the end of injection will tend to decrease with time, because of two reasons: (1) soil compression till reaching equilibrium, and (2) tendency of the excess water trapped in the grout to bleed into the soil as the grout itself shrinks. The occurrence of upheave and its variation with injection and with time therefore depend on the soil compressibility characteristics, the grout rheological characteristics and the injection procedure (especially the injection rate). The remaining part of this section discusses for the test soil and procedure considered herein, as well as for the standard TGC grout material, the occurrence of soil surface upheave and its variation during injection and suspension.

The variation of upheave with injection may be understood by examining the results of the last three stages that were upheave-inducing. For these stages, the following observations can be made (see Fig. 6):

- Upheave did not occur immediately after starting the injection into the sandy soil. However, it occurred after reaching a certain degree of improvement.
- For the procedure of alternate injection and suspension, as considered herein, the upheave increases at a practically constant rate during the injection of a given stage.
- The rate of upheave increase during injection increases with stage injection.
- Once the injection is suspended, the attained upheave decreases gradually with time as a result of creep deformation until reaching equilibrium.
- During suspension the soil particles get in a more compact and stiffer structure (than that of the particles at just before the suspension) as may be represented by the creep deformation. A post-suspension resumed injection into a more compacted soil results in a larger contribution of the injection to the upheave. This is corroborated by the decreasing volume change of soil during both of injection and suspension and the increasing rate of upheave with stage injection. It is interesting to note that there was almost no volume change of the soil during I-5, which implies that the injection was almost entirely contributing to the upheave.

6 CONCLUSIONS

In this paper, the TGC method was examined through physical modeling in the laboratory using a large-scale double-wall calibration chamber and a commercially available injection system. The used systems were described in the paper and typical results of injection into sandy soil were presented. These results were then discussed to illustrate the effectiveness of the method in improving the soils and in compensating the ground settlement. Based on the presented results and discussions, the following conclusions can be made on the performance and effectiveness of the TGC method:

- During injection, the soil exhibits significant deformations and increases in the lateral stress. For the soil and stress levels considered herein, the test soil experienced gradual transition from settlement to upheave during injection. After termination or during suspension of injection, the soil experiences creep deformation and relaxation of the lateral stress till reaching equilibrium. The suspension of injection does not significantly influence the increase of lateral stress with resumed injection. However, the soil deformation due to injection of a given grout volume depends on the deformations experienced during both of injection and suspension.
- The coefficient of earth pressure at rest, K_0, increases continuously with injection and has a practically linear relationship with the injected volume of grout (for the soil, procedure and grout volume considered in this paper).
- The soil improvement due to treatment by the TGC method in terms of soil volume change (that is the change of volume of voids) increases continuously with injection. The improvement increases practically linearly with the injected grout volume till the occurrence of soil surface upheave. Then, with continued injection (upheave-inducing injection) the improvement increases at a decreasing (attenuating) rate.
- For the settlement compensation works in sandy soils, the occurrence of upheave should be expected after reaching a certain degree of improvement. After the onset of upheave, continued injection results in a gradually increasing rate of soil upheave. Once the injection is suspended, the attained upheave decreases gradually with time as a result of creep deformation until reaching equilibrium.

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