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Development of compensation grouting modelling and control system

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ABSTRACT: Modelling compensation grouting operations is necessary to make an efficient design of compensation work, where decisions are needed for grout spacing, injection volume and injection rate. Simulation of grouting operation within the framework of tunnel construction analysis requires some idealisation because of the difference in scale of each process. In this study, numerical modelling of a single grout injection process was performed and the issue of soil consolidation affecting the efficiency of compensation grouting is addressed. New modelling software, which can simulate and analyse tunnel excavation and compensation grouting operations, has been developed. This modelling software is part of the new compensation grouting control system, which assists the set-up of a compensation grouting scheme during the tunnelling design stage. It is also used during the construction stage to refine the predefined grouting scheme on the basis of the daily information collected on the site.

1 INTRODUCTION

When grout is injected into clayey ground, the soil around the grout injection point expands. This type of grouting is often done when large ground movement is expected to happen during tunnel construction and excavation. The grout injection can 'compensate' for stress relief and associated ground settlement. This operation is often called compensation grouting.

Modelling compensation grouting operations is necessary to make an efficient design of compensation work, where decisions are needed for grout spacing, injection volume and injection rate. Unfortunately, the current design method is still largely empirical and the prediction of grouting quantities still depends on crude empirical formulas, which are in general unable to match with complex situations such as interaction with existing buildings and tunnels under construction. Hence, there is a need to develop a tool that models, simulates and controls the complex operation of compensation grouting. It is also essential that the assumption used in compensation grouting modelling is based on fundamental understanding of the mechanisms of grouting process.

The study presented in this Paper is part of on-going COSMUS (Real-time Modelling and Compensation of Soil Movements on Underground Sites) project funded by the Brite-Euram Programme of European Commission. The main tasks of the Project are (i) to develop software that can simulate compensation grouting under tunnel construction, (ii) to develop a control system for compensation grouting, and (iii) to develop a monitoring system of fibre optic sensors. The Paper describes the summary of the first two tasks.

2. COMPENSATION GROUTING MODELLING

2.1 *Local Phenomenon vs. Global Phenomenon*

Injection of grout is a small-scale phenomenon (10-100 mm order), whereas tunnel excavation process is a large-scale one (larger than 1m order). In order to simulate the grout injection process using the finite element or difference methods, the size of the elements needs to be small enough to capture the plastic deformation of soils surrounding a grout injection point. On the other hand, when the grout injection process is incorporated into tunnel excavation analysis, modelling each grout injection process is not computationally economical. Hence, there is a need to develop a soil-grout homogenisation method, which can be used in large-sized finite elements in order to reduce the computational demand but still able to capture the small-scale soil deformation behaviour associated with grout injection process.

2.2 *Local Modelling*

The actual behaviour of grout displacing the surrounding soil is a very complicated one. However, the grouting process is commonly categorised to be either compaction grouting or fracture grouting (Mair, 1994). Although the term compaction grouting is usually reserved for grouting process in cohesionless soils, it is possible that this process can occur in cohesive soils when injection volume is small and high viscosity grout is used. Compaction grouting forms a coherent bulb around the point of injection. As the injection volume increases, the soil around the grout deforms plastically due to high injection pressure. Subsequently, this plastic deformation may accelerate locally or hydraulic fracturing may suddenly occur, leading to penetration of grout in fingers, thin sheets or lens patterns. This is so-called fracture grouting.

In most cases, grout injection process is rapid and the clay surrounding the injection point deforms in an undrained manner. As the soil deforms plastically due to the large injection pressure, excess pore pressure will generate around the injection point. This excess pore pressure then dissipates with time and the clay consolidates. Consequently the ground starts to settle, reducing the compensation effort achieved immediately after injection. This consolidation process results in an adverse effect in terms of the effectiveness of compensation grouting.

The rate of consolidation depends on the area and magnitude of excess pore pressure generated during injection and the permeability and compressibility/swelling characteristics of the clay. Since the area of excess pore pressure generated is usually localised around the injection point, the hydraulic gradient within the plastic zone is expected to be large. Hence, consolidation can occur in a rather short period (i.e. possibly within the construction period) compared to longer-term consolidation due to tunnelling or excavation. It is therefore important to assess the effect of consolidation on the efficiency of compensation grouting.

2.3 *Assessment of Grout Efficiency*

The effect of excess pore pressure generation and subsequent soil consolidation on compensation grouting was investigated by finite element modelling of cavity expansion type grouting. The model parameters investigated were soil properties (compressibility and swelling characteristics, critical state angle and permeability), injection volume, initial condition (confining pressure and overconsolidation ratio), and initial cavity diameter.

The modified cam-clay model was used to simulate the clay behaviour. A single grout injection forming a spherically shaped grout in an infinite soil body was modelled. Typical size of the elements used was in the order of 10 cm, so that the local phenomenon of soil expansion can be examined. The initial stress condition was assigned to be isotropic and the confining pressure was applied at the outer boundaries of the model. The grout injection process under more complicated and realistic conditions, such as multiple injections, anisotropic in-situ stress condition, non-spherical grout shape, fracture initiation and surface boundary effects, is currently being investigated and will be reported in the future.

In this study, the "grout efficiency factor" is introduced to quantify the effectiveness of compensation grouting. The grout efficiency factor η_c is defined as the ratio of the volumetric expansion during consolidation to the initial volumetric expansion, which is equal to the injection volume V_0.

$$\begin{aligned}\eta_c &= [(r_0 + dr)^3 - r_0^{\,3}]/[r_0 + dr_0]^3 - r_0^{\,3}] \\ &= (3/4)\pi[(r_0 + dr)^3 - r_0^{\,3}]/V_0 \qquad (1)\end{aligned}$$

where r_0 is the initial radius from the centre of the spherically shaped grout, dr is the radial displacement at $r = r_0$ at a given time t, and dr_0 is the radial displacement immediately after injection.

Immediately after injection, the expansion is made in undrained condition. Hence, the grout efficiency factor at any point in space is one as shown in Figure 1. As the soil starts to consolidate, dr in Equation (1) becomes smaller than dr_0 and the grout efficiency factor decreases with time.

As shown in Figure 1, the decreasing rate of the grout efficiency depends on the distance from the injection point. At the end of consolidation, the grout efficiency factor becomes a stationary final value. Therefore, the grout efficiency factor is a function of time as well as space.

The final grout efficiency factor becomes independent of space from a certain distance from

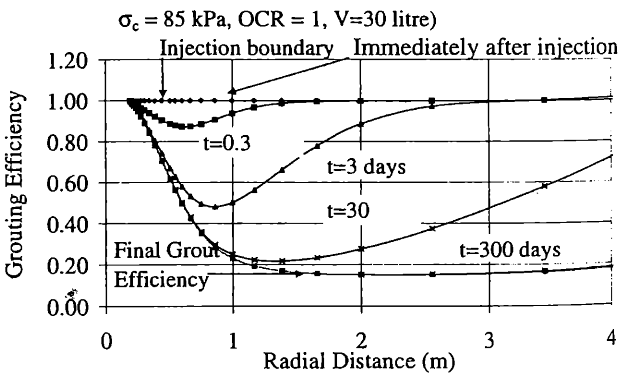

Figure 1. Changes in grout efficiency factor with time.

the injection point (Radial distance $r > 1.5$ m for the case shown in Figure 1). In theory, this distance is where the plastic/elastic boundary exists for overconsolidated soils. In this study, this boundary was determined arbitrarily to be the location where the excess pore pressure is 0.01% of the excess pore pressure generated at the injection boundary. The volume occupying this boundary (called 'seepage volume' in this study) will consolidate, resulting in decreasing grout efficiency with time.

The magnitude of 'seepage volume' is largely controlled by overconsolidation ratio (OCR) of the soil and injection volume. Figure 2 shows the ratio of seepage volume to injection volume plotted against OCR. It was found that other model properties did not have large effect on the values of the normalised volume ratio.

It was also found from the parametric study that OCR of the soil largely controls the value of the final grout efficiency, as shown in Figure 3. Variation of other model parameters, such as the compressibility/swelling characteristics of the soil, injection volume, and confining pressure, did not change the final grout efficiency value considerably.

2.4 *Grout Efficiency-Normalised Time Factor Relationship*

In this study, the decreasing rate of grout efficiency factor with time due to the consolidation effect is expressed as a function of the normalised time factor T_g defined as

$$T_g = k\sigma_c t/\kappa\gamma_w d^2 \tag{2}$$

where k is the permeability, σ_c is the confining pressure, t is the time, κ is the Cam-clay swelling index, γ_w is the density of water and d is the radial distance.

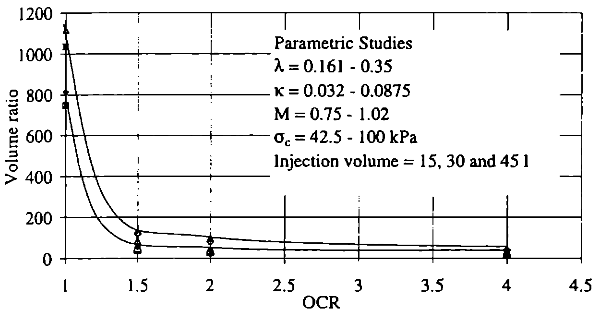

Figure 2. Ratio of seepage volume to injection volume versus OCR.

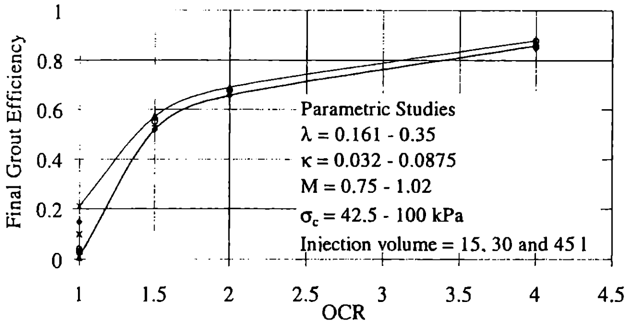

Figure 3. Final Grout efficiency versus OCR.

Using the data outside the 'seepage volume', the time dependent grout efficiency is plotted against the normalised time factor as shown in Figure 4. Since the region outside the seepage volume does not contribute to the consolidation effect on grout efficiency, there will be a unique grout efficiency-normalised time relationship for a given set of input model parameters. Again, OCR is the major controlling factor of the grout efficiency–normalised time relationship.

The transient component of the grout efficiency $\eta_c = (\eta_{c,Tg} - \eta_{c,final})$ can be normalised by the ultimate efficiency loss $(1 - \eta_{c,final})$ thus:

$$\eta_{c,\,normalised} = (\eta_{c,Tg} - \eta_{c,final})/(1 - \eta_{c,final})$$
$$\text{or} \quad \eta_{c,Tg} = \eta_{c,final} + \eta_{c,normalised}(1 - \eta_{c,final}) \tag{3}$$

where $\eta_{c,Tg}$ is the grout efficiency at normalised time factor T_g, and $\eta_{c,final}$ is mainly a function of OCR as shown in Figure 3. Figure 5 shows $\eta_{c,normalised}$ dropping from 1.0 (for $T_g < 0.01$) to 0 (for $T_g > 1$) irrespective of OCR, etc. In this way, the effects of time and distance can be uncoupled from those of OCR.

2.5 *Global Modelling of Grouting Process*

In global modelling of tunnel construction and compensation grouting in clayey ground, numerical analysis is performed in undrained conditions. This is because the excess pore pressures generated by tunnel excavation take a long time to dissipate (months to years). As described in Section 2.2, on

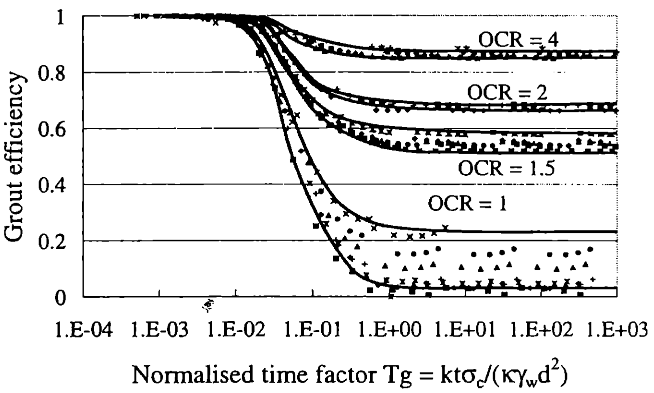

Figure. 4 Grout efficiency versus normalised time factor.

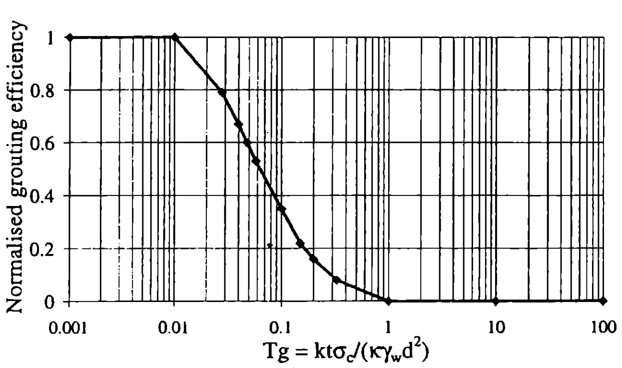

Figure. 5 Normalised grout efficiency η_c versus normalised time factor T_g.

the other hand, the excess pore pressures developed during grouting operations dissipate much faster (within days and weeks) because of smaller drainage length and larger hydraulic gradient. The liquid in the grout may bleed out rapidly as the grout solidifies. Therefore, the assumption of undrained conditions used in global modelling may not be valid for grout injection modelling.

Global effects of compensation grouting can be modelled by increasing the volume of finite elements in which the injection points are located. The expansion of the elements is achieved by reducing its compressibility to an artificial value from the nearly incompressible condition (Poisson's ratio close to 0.5) and applying artificial internal pressure inside these elements.

The expansion pressure applied in the soil-grout element is increased gradually until the increase in the element volume becomes equal to a predefined value. The amount of volume expansion of the element should be related to grout efficiency as follows.

$$[\textit{Volume expansion}] = \eta \bullet [\textit{Injection volume}] \qquad (4)$$

where η is the grout efficiency. The value of η depends on consolidation effect η_c described in Section 2.4, shrinkage of the grout itself, and escaping of grout to the far field. Therefore, in practice, the value of η applied in the analysis will be set empirically through in-situ preliminary trials as well as from the knowledge obtained in the local modelling task described above.

The artificial expansion pressure can be applied either in isotropic conditions to simulate compaction grouting process (bulb expansion) (Figure 6a) or in a certain direction perpendicular to the plane of fracture propagation to simulate hydrofracturing grouting process (Figure 6b).

In general, cavity expansion grouting is applied in small injection cases, whereas hydrofracture grouting is generally observed in overconsolidated clays and horizontally bedded soils. From observations made in the field, the user can decide which model to use. The properties of the grout (viscosity, injection pressure, injection rate) can also be determined to control the manner in which the grout penetrates the soil and the way in which it creates displacement (Baker et al., 1983 ; Mair, 1994 ; Kimmance et al., 1995).

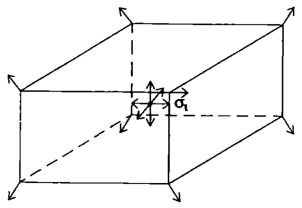

Figure 6a. Cavity expansion grout modelling.

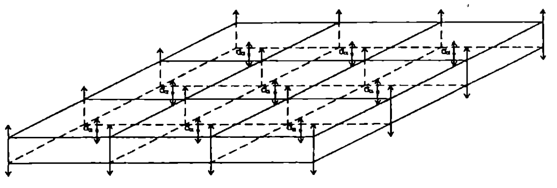

Figure 6b. Hydrofracture grout modelling.

After the volume expansion step simulating grout injection operation, it is necessary to release the artificial internal expansion pressure but to keep the expanded volume in order to continue the analysis under post-grouting condition. This can be achieved by defining the expanded grout-soil elements back to the nearly incompressible condition before releasing the internal pressure. It is possible that the shear stiffness of the grout-soil element becomes larger than the original one because of additional inclusion of solid grout acting as reinforcement in the soil (Hawlader and Soga, 1999). The stiffness of the elements can be modified to take this change into consideration.

2.6 *Modelling tool of tunnel construction and compensation grouting*

It is evident that the analysis of combined tunnel excavation process and compensation grouting operation is a complex three-dimensional problem. In this study, a new modelling technique called the « Steady State » model has been proposed to simulate an advancing tunnel heading. This new technique consists of fixing the tunnel face centred inside the grid mesh and progressively shifting all data concerning geology, buildings and grouting as well as the stress and strain states in the opposite direction of the advancing tunnel. At the model boundary that is facing the tunnel front, new data stored in a specific external database are introduced (geology and structures) continuously.

Using this method, the size of the model can be restricted to the longitudinal and transversal extent of the settlement trough, reducing the computational demand. Simple well-known relationships (such as those proposed and documented by Peck (1969), O'Reilly & New, 1982 ; Rankin, 1988; Mair and Taylor, 1997) allow to predict the theoretical dimensions of the settlement trough with respect to the tunnel axis depth and the soil type in order to determine the model size.

This new tunnelling modelling technique has been implemented using the FLAC3D finite difference code (Itasca Consulting Group Inc., 1997). A typical grid mesh used in the analyses is shown in Figure 7.

The structural behaviour of the tunnel support is represented by rings of "shell" elements. The presence of buildings is simulated by loads applied at the right nodes according to the foundation locations, where the structural stiffness is negligible. On the contrary, a considerable structural stiffness is simulated controlling the movement of nodes "belonging" to the building so that they are globally displaced following the foundation plane.

The compensation grouting modelling described in the previous section has been incorporated into the Steady-State model. Although the actual principle of compensation grouting is to introduce grout into the ground between a structure and the tunnel at the same time as tunnelling construction, each process is modelled separately at each time step.

3. COMPENSATION GROUTING CONTROL SYSTEM

A new computerized system called ContAcTS (Control of Active Tunnel Settlements) was developed in the Project to assist the set-up of a compensation grouting scheme during the tunnelling design stage and to refine the predefined grouting scheme on the basis of the daily information and computer prediction during the construction stage (see Figure 8).

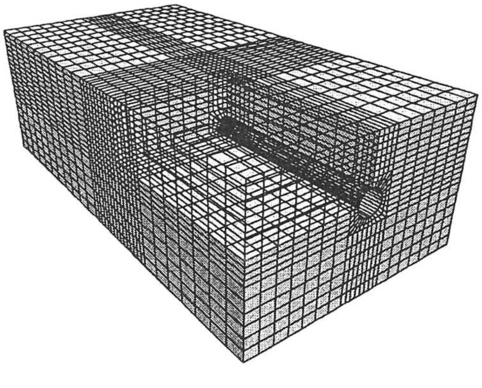

Figure 7. Typical grid mesh used in the analyses.

Compensation grouting requires a repeated injection of small quantities. Grouting instructions must be revised daily according to the advance of tunnelling, and even during the day a continuous adjustment is necessary to account for observed structural movements. As part of ContAcTS, new software called COGNAC was developed for compensation grouting control and it has the following functions:

- first-level prediction of structural movements, using classical theories developed by Peck (1969). These predictions do not really account for the exact soil characteristics, but can provide a good approximation in simple cases,
- interface with the 3D soil model described in the previous section,
- conversion of these movements into a map of grouting quantities via the 'grouting efficiency' factor, which characterises the quantity of grout necessary to obtain a unit volume of soil heave,
- daily generation of the grouting programme, and
- update the map of the 'grouting efficiency' factor from daily observations of structural movements.

Very large numbers of sensors can be involved on a single site (e.g. more than 2500 sensors or survey points on the sites of the Jubilee Line Extension Project in London); the volume of the database can rapidly involve millions of measurement data. Therefore, a relational database was carefully designed and optimised to ensure the best performance level at every stage. This database is included in a new monitoring system called GEOSCOPE, which is used to control the movements of the soil body and of the structures in real-time. GEOSCOPE has the following features.

- a complete set of intelligent fibre sensor linked by means of a field bus,
- an acquisition software,
- extensive functions to trigger alarms to be taken in account by the grouting system, and also to be dispatched by fax and/or pager,
- a real-time graphic display giving an instant view of the deformations,
- a specialised software with comprehensive tools to analyse and produce reports, and
- communication tools in order to be able to connect remote data acquisition units.

ContAcTS was used successfully for a subway construction in Puerto Rico. More details of the system can be found in Buchet et al. (1999).

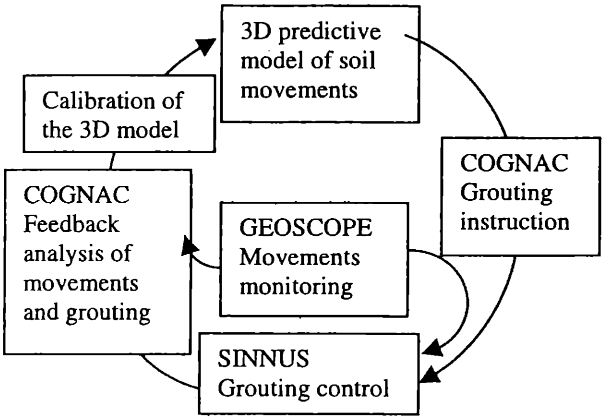

Figure 8. Compensation Grouting Control System.

4. CLOSURE

A new compensation grouting modelling and control system has been developed under the COSMUS project funded by European Commission Brite Euram Programme. The modelling of compensation grouting operations within the framework of tunnel construction analysis requires some idealisation because of the difference in scale of each process. In this study, a single grout injection process forming a spherically shaped grout was investigated and it was found that the effect of consolidation on grout efficiency can be assessed by the normlised time factor and grout efficiency relationship. Using this relationship as well as the information obtained through in-situ preliminary trials, compensation grouting modelling can be incorporated into tunnel construction analysis by expanding the elements in which the grouting points exists. The amount of volume expansion is determined from the injection volume and grout efficiency factor.

The modelling software is part of the new compensation grouting control system, ContAcTS, which allows to assist the set-up of a compensation grouting scheme during the tunnelling design stage and to be used during the construction stage to refine the predefined grouting scheme on the basis of the daily information collected on the site (actual soil and structure displacements, amounts and locations of injections, tunnelling parameters).

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