Large consolidation and experimental ageing of cement-based grouts
Grande déformation et vieillissement des coulis à base du ciment

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ABSTRACT

This paper describes a study of large consolidation of cement-based grouts. Bleeding (drainage) and efficiency (volume) losses result from reductions in the grouts water content under grouting (injection) pressures and soil compaction. Water content losses due to hydraulic drainage are found to be dominant in a standard consolidation and that the losses due to hydration (ageing) of the cement mix are negligible. This justifies use of small or large consolidation models to predict bleeding behaviors for this class of grouts. Comparisons with a previous experimental study show the large deformations solution to produce slight improvements to predictions. Improvement is expected to be more pronounced under true two or three dimensional strain conditions as in compaction and compensation grouting.

RÉSUMÉ

Cet article décrit une étude sur la consolidation des coulis à base du ciment. La perte de l'efficacité en termes de réduction du volume du coulis pendant un jointoiement résulte des réductions de la teneur en eau de coulis sous la pression d'injection et du tassement de sol. Dans une consolidation conventionnelle, des pertes de la teneur en eau du coulis dues au drainage hydraulique s'avèrent prédominantes tandis que celles dues à l'hydratation (vieillissement) du mélange sont négligeables. Ceci justifie l'utilisation du model dit de Petites ou Grandes déformations pour prédire le drainage hydraulique de cette classe de coulis pendant le jointoiement. La comparaison avec une étude expérimentale précédente montre que le model dite Grande déformations améliore légèrement les prévisions. On s'attend à d'avantage d'amélioration de prévisions par ce model en deux ou trois dimensions.

Keywords : cement, grout, hydration, bleeding, large consolidation, ageing, finite element

1 INTRODUCTION

A recent experimental study (Bangoyina & Karim, 2007) showed that the water content, consistency and vane shear characteristics of cement-based grouts were only slightly affected by experimental ageing. Experimental ageing is defined in the context of this research as the loss of water in a grout sample due to hydration in a standard consolidation-type experimental set-up within a short test period. Main results from these tests will be briefly revisited but the focus of this paper is on the analytical and numerical bleeding predictions of such grouts. The significance of those results is important in two respects. It gave more confidence in the earlier tests on bleeding-viscosity relationships of the same grout mixtures reported in Geotechnique by Gustin, et al 2007: cement-hydration errors where marginal. Also, it justifies use of Tarzaghi's (1943) small and Gibson's et al (1967) large consolidation theories for predicting the bleeding process: bleeding is predominantly a hydraulic drainage process as in cohesive soils.

In this paper analytical and finite element results using small and large deformation assumptions are reported. The research work is aimed to improve soil-grout interaction predictions and develop more efficient grout design for applications in (compensation) fracture grouting and permeation grouting. Because the grout has a relatively high mobility, results are less applicable for the (low mobility) compaction type of grouts.

Recent practice on grouting where cement-based grouts are common is found in James (2004). Field complexities are simplified in this study to an analogues grout element at the grout-soil contact boundary (Figure 1). The material characteristics and assessment of ageing effects of that element was carried out using standard soil consistency, strength and consolidation testing followed by the analytical study.

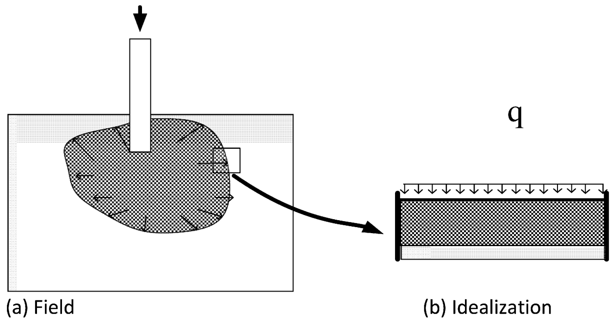

Figure 1. Field and experimental idealization.

2 SUMMARY OF AGEING TEST RESULTS

Effects of ageing on the grout strength and consistency were studied with standard soil laboratory tests (vane shear VS, particle size distribution PSD, and fall cone FC).The type of cement used is composite Portland cement type (CEM II/B-M/V-L; ENCI). The VS test is motorized with a rotation rate of 90 degrees per minute according to the British Standard BS1377: Part 19906 with vane size 24 by 24 mm. The FC tests were carried out using British Standard BS1377: Part 2:19904.3. De-aired water and cement were placed in the same environment (laboratory) 24 hours before the test to avoid a temperature difference between the two materials when preparing the samples. Mixing with de-aired water at different

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void ratios of 0.35-1.18 for three minutes was followed by VS, FC or conventional consolidation testing. At least 6 VS ageing and two series of FC tests were recorded for each value of these initial void ratios. Bangoyina & Karim (2007) reported these tests and presented shear strength and liquid limit relationships with void ratios for their grout mix. They concluded the following:

i- PSD tests: The grout mix consisted of 91% fine-sized cement materials (81% Silt- and 16% Clay-size particles).

ii- VS tests: Shear strength of the material with initial void ratios between 0.7 and 1.18, remains constant during the first 100 min. with maximum increase of less than 4% during this dormant (no hydration) period. The undrained shear strength of samples at these void ratios ranged from 4 to 20 kPa within 24 hours, equivalent to "soft to very soft fine-grained soils".

iii- FC tests: The Liquid limit is around 30% equivalent to a classification "soil of low plasticity". FC penetration remained constant for 100 minutes decreasing from an average of 25mm over a 4 hour period after a 100 m first dormant period. The first and second dormant periods (Chen, 2007) extend to several hours to a day for the type of cement used. Most of the tests in this study fall within the first inert phase of that period.

iv- Viscosity tests (Gustin et al, 2007): The initial low plasticity and high water content of the grouts are expected to result in large deformations at full consolidation and a measurable rate of viscosity change. During this short time to full consolidation the hydration (cementing) process will be less significant than the mechanical consolidation process (reduced water pressures due to bleeding combined with increased effective stresses). The published relationships bleeding efficiency-water/solids ratio-viscosity are therefore valid for the study which basically repeats the same grout mixes. Values of viscosity ranged from 20 up to 100 mPa.s, corresponding to the range of void ratios and water content (water-solid ratios) of the test samples from start to end of consolidation.

It follows that a cement-based grout used in this way may be considered as fully saturated Clayey Silt or very Silty Clay. Mechanical consolidation models for cohesive soils and standard Oedometer testing are therefore suitable as long as the aeging period is within 2 to four hours. Basic models from soil mechanics could therefore be assumed to represent the grouts (2-phase material, effective stress concept, cohesive-frictional shear behavior, Mohr-Coulomb relationship, large-strain consolidation). Visco-plastic stress-strain models are applicable also in soil mechanics and materials like cement paste for describing the viscous behavior for the dormant period.

Ageing of the grout will have a no effect at all on the viscosity of the material within 100 minutes where hydration effects are minimal. The drainage and plasticity characteristics of the grouts used in this study are expected to be similar to those of Silt with low liquid limit and high water content. The permeability range for this material given the high water/solids ratio is expected to result in full consolidation, of a thin (2 cm) sample, within less than 4 hours for the samples with the highest cement/water ratios. This was in fact less than 100 minutes for the most tests.

3 LARGE CONSOLIDATION ANALYSIS OF GROUTS

When large strains take place in soft materials under high pressures, the pores volume is significantly reduced resulting in decrease in the void ratio that is non-linearly (geometrically) related to the effective stress increase. A smaller void ratio means that water has less room to flow and this a results in a decrease in the permeability and drainage with time. Gibson et al (1967) expressed the consolidation problem of soft soils considering large strain deformations, nonlinear compressibility and variable permeability as follows.

$$\left(\frac{\rho_s}{\rho_f}-1\right)\frac{\partial}{\partial e}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k(e)}{\rho_f(1+e)}\frac{\partial \sigma}{\partial e}\frac{\partial e}{\partial z}\right]+\frac{\partial e}{\partial t}=0 \quad (1)$$

Where: ρ_s is density of fluid, ρ_f density of solid with contact (effective) stresses of σ, and permeability k (function of the void ratio e). Solution to this highly non-linear equation in the z-dimension and time t is obtained using simplifying assumptions. When permeability and compressibility are constant, for small strains, this equation yields Terzaghi's consolidation equation.

The analytical solution of Xie *et al* (2004) is used in this study. Exact solution of the large consolidation governing equation is provided only for one-dimensional consolidation assuming constant permeability and compression parameters. The validity of using the consolidation model of Gibson has been justified in this work for cement–based grouts. Consolidation of the grout during the experimental ageing is mainly due to the bleeding phenomena rather than to chemical reaction of the cement with water.

In the following key equations describing large and small consolidations the derivation steps combining Gibson's and Xie's solutions have been omitted and can be found in the quoted references. A variable coefficient of volume compressibility m_v may be computed per new increment i for sample thickness h_i, using parameters of a previous increment, from:

$$m_v=-\frac{1}{1+e_{i-1}}\left(\frac{e_i-e_{i-1}}{\sigma_i-\sigma_{i-1}}\right)=-\frac{1}{h_{i-1}\left(\frac{h_i-h_{i-1}}{\sigma_i-\sigma_{i-1}}\right)} \quad (2)$$

To obtain a good estimation of the compressibility, small deformation (strain-controlled) or small stress increments (stress-controlled) have to be applied in *n* small steps. According to Xie[6] the excess pore water pressure u_e resulting from a boundary pressure q at depth z due to large strains is:

$$\frac{1}{\gamma_w}\frac{\partial}{\partial z}\left[\frac{k_v(1+e_0)}{1+e}\frac{\partial u_e}{\partial z}\right]=m_v\frac{1+e}{1+e_0}\left[\frac{\partial u_e}{\partial t}-\frac{\partial q}{\partial t}\right] \quad (3)$$

Equations (2) and (3) are solved iteratively using a numerical routine, in our case a Matlab-FEM procedure, or analytically assuming constant material parameters with t and z.. Equation (3) is stated often in the following form (using subscript g to indicate a grout) assuming constant material parameters:

$$\frac{\partial u_{eg}}{\partial t}=c_v\frac{\partial^2 u_{eg}}{\partial z^2} \quad (4.a)$$

where,

$$c_v=\frac{k_{vg}}{m_{vg}\gamma_w}\left(\frac{1+e_{0g}}{1+e_g}\right)^2 \quad (4.b)$$

$$m_{vg}=\frac{c_c}{1+e_{0g}}\frac{\log(\sigma_g-\sigma_{0g})}{\sigma_g-\sigma_{0g}} \quad (4.c)$$

The mathematical model for large strain consolidation becomes after some manipulations using equations 4:

$$\frac{\partial u_{eg}}{\partial t}=\left[\frac{k_{vg}}{\gamma_w.c_c}\frac{(1+e_{0g})^3}{(1+e_g)^2}\frac{(\sigma_g-\sigma_{0g})}{\log(\sigma_g/\sigma_{0g})}\right]\frac{\partial^2 u_{eg}}{\partial z^2} \quad (5.a)$$

And, for one-dimensional small strain consolidation:

$$\frac{\partial u_{eg}}{\partial t} = \frac{k_{vg}(1+e_{0g})}{\gamma_{w}.c_{c}} \frac{(\sigma_{g}-\sigma_{0g})}{\log(\sigma_{g}/\sigma_{0g})} \frac{\partial^{2} u_{eg}}{\partial z^{2}} \quad (5.b)$$

Xie derived the large-strain settlement (s_{ld}) closed-form solution to 5.a. for a layer of drainage path H_{dr} and thickness H expressed for a grout consolidating (bleeding) under effective pressure σ_g using non-dimensional time factor T_{vg}=t. c_{vg}/H_{dr}^2:

$$s_{ld} = H(1-\exp(-m_{vg}\sigma_{g}))\left(1-\sum_{M=1}^{\infty}\frac{2}{M^{2}}\exp(-MT_{vg})\right) \quad (6.a)$$

Terzaghi's theory yields small-strain settlement s_{sd}:

$$s_{sd} = Hm_{vg}\sigma_{g}\left(1-\sum_{M=1}^{\infty}\frac{2}{M^{2}}\exp(-MT_{vg})\right) \quad (6.b)$$

The solution of these equations requires the coefficients of permeability and that of volume compressibility of the used grout mixtures. These coefficients were determined experimentally by Gustin et al (2007): c_c=0.1; k_{vg}= $1.2\times10^{-7}\,m/s$. These values were updated per increment using equations 2 and 4 in the large strain FE solutions. The drainage boundary condition for all the tests is single bottom drainage. Rigid filter stones of different permeability larger than that of the grout had no apparent effect on the results indicating no drainage boundary conditions change during bleeding.

4 ANALYSIS OF THE RESULTS

The Partial Differential equations Tools (PDE tools) of the standard software Matlab is used to solve equations (5a) and (5b) numerically based on the finite elements method (FEM). A linear-strain finite triangulation of the computational domain was generated with a triangle quality of 0.976 as determined from the Bank & Randolph (1990) method. Single bottom drainage, initial and loading boundary conditions, and smooth boundaries (no lateral movements on sides and no vertical bottom displacements) were specified as input boundary conditions. Iterations were repeated to optimize the time and load steps to minimize numerical errors.

Results from the large and small consolidation models (equations 5) show the difference in drainage predictions. For the same grout water-cement ratio, at the same time interval Figures 2 and 3 show a slightly more rapid decay of excess water pressure with depth from large deformations. In other words the traditional small consolidation model of Terzaghi (solution 5b) is more conservative in predicting the rate of pore water dissipation. The series of numerical tests yielded up to 15% differences in the pore pressure and degree of consolidation predictions (see figure 4). This difference is expected to be higher in two and three-dimensional analysis as in field grouting.

Compaction grouting forming cylinders or balls of grout (2-Dimensional problem), and compensation (fracture) grouting (a three-Dimensional problem) are typical cases. Non-linear large deformation (geometrical) effects are more pronounced in a multi-dimensional stress field than in one-dimensional problems. It implies that bleeding under large pumping pressures with large deformations of the grouts occurs more rapidly in the field than that predicted by the simplified model of figure 1. It is possible also to imagine that effect physically if one confines the injection of grout in one direction by preventing grout spread in the other directions. That will lead to higher pore pressures that take longer time to dissipate (bleeding will be slower).

Reduced permeability and compressibility of the grout from large deformations will lead to stiffening effect as deformations increase but eventually geometric nonlinearity will be less pronounced and the solutions 5a,b approach each other. This effect is clearly seen in Figure 4. From the beginning of the consolidation up to a time factor of about 0.0025, the discrepancy between the degrees of consolidation of the two models is around 10% diminishing progressively to less than 5 % around 95% consolidation. The same tendency is observed for all the grouts in this study. Most encouraging in these results is the fact that the experimental results (shown here for one sample) as carried out by Gustin et al (2007) are closer to the Large strain numerical results using equation 5a.

Our findings are in general agreement with those of Xie at al. (2004). There large strain analysis of one-dimensional consolidation of saturated and homogenous clays shows faster dissipation of excess pore water pressure than in small strain consolidation. They also found that the discrepancy between large and small strain theories diminishes with reducing compressibility m_v. Their analytical (exact) solution and constant geotechnical properties for soft clays compare exactly to our solutions but this author used a numerical (approximate) solution and variable geotechnical properties representing a cement-based grout to produce the solutions in figures 2-4.

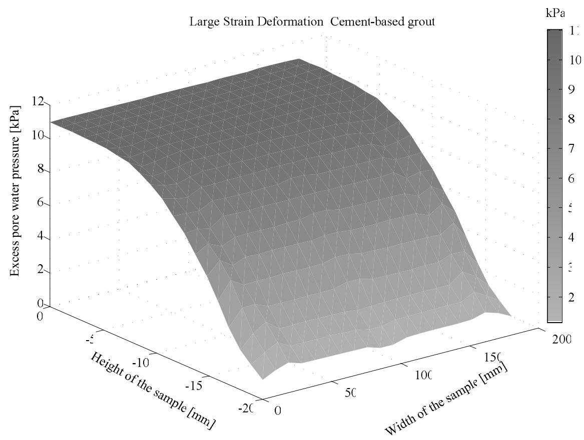

Figure 2. Excess pore water pressure (large deformation).

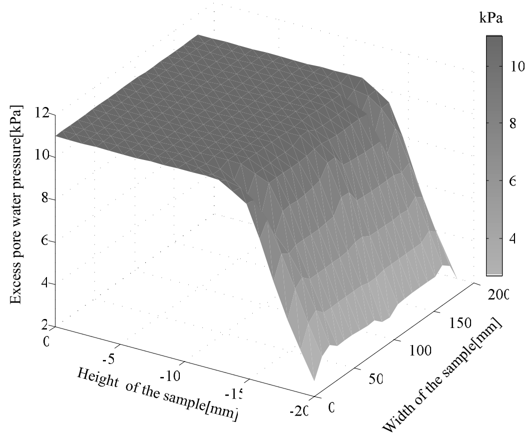

Figure 3. Excess pore water pressure (Small strain deformation).

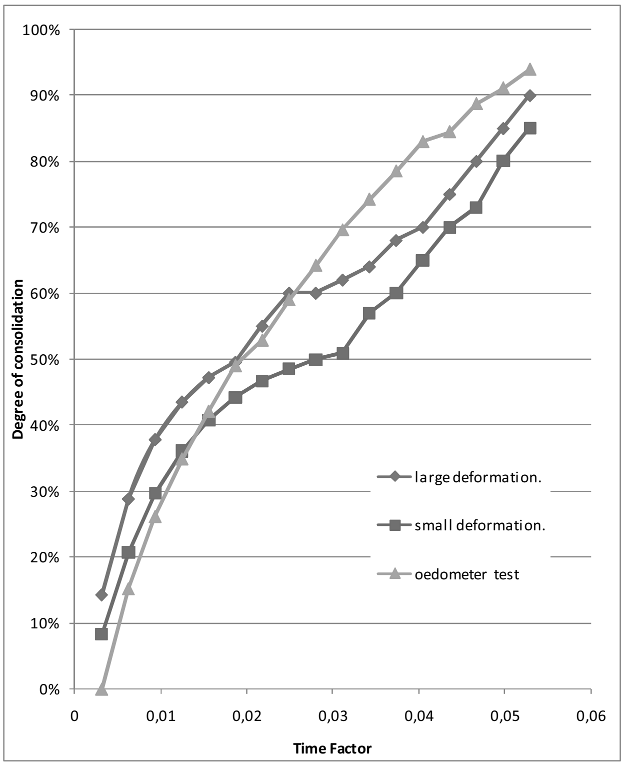

Figure 4. Experimental and numerical consolidation results.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

A previous comprehensive program of consolidation testing of cement-based grouts was followed by tests for the effect of experimental on consistency, strength and plasticity. Aging was found to have negligible effects for the most test periods. This confirmed the validity of the previous consolidation (bleeding) test results and demonstrated that hydration errors were minimal during bleeding. The water-cement ratio-viscosity-bleeding relationships of Gustin at al. (2007) are therefore valid for the range properties in this analytical study.

The Large deformation FE solution of this class of problems has demonstrated the better accuracy and closeness to the experimental test results. This is expected to be more so when field grouting is studied in two- and three-dimensional field situations.

The next research phase is on the grout-soil interaction problem. One expects that the grouting process from permeation to fracturing (compensation) to compaction is controlled by relationship between the state parameters of both the soil and grout. An extension to the experimental setup has been designed to include grout-soil interaction to investigate the controlling mechanism and parameters of the problem to improve the grout design and predictions methods. The authors suggest investigating this problem further using a setup in which the grouting process and its parameters can be fully monitored. Further research is needed to investigate the discrepancy between our simple model, a simple one-dimensional soil-grout interaction model and real grout-soil interaction behavior in two and three dimensions.

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