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THMC MODELLING OF JET GROUTING

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Abstract. A framework for the study of the jet-grouting hydration reaction and of the associated thermo-hydro-mechanical and chemical (THMC) interactions with the surrounding soils has been developed. In this work, we summarize the basic formulation that may be used for the simulation of such interactions, including references to the balance equations governing the problem, to the release of heat during the curing of the jet-grouted mass, to the TMC behaviour of such material and to the THM behaviour of the surrounding soil. The approach presented falls within the framework of plasticity for saturated soils, and it has been implemented within a FEM code for the study of the potential effects of the THMC couplings associated to jet-grouting treatments. The results obtained with this program validate it as a proper tool for the systematic analysis of a number of questions of interest in engineering practice, allowing the assessment, among others, of the following issues: magnitude and rate of production of the thermo-plastic settlements caused by the heat release associated to the installation of jet-grouted columns in the soil; effects of the release of the hydration heat on the hydraulic conditions in the surrounding soil; effects of the boundary conditions, the relative position of the jet-grouted zones and its sequence of installation on the rate of increase of the stiffness and strength associated to the curing of the jet-grouted zones; effects of those factors on the impact of the heat release on the surrounding soils.

1 INTRODUCTION

A number of factors, variables and effects must be simultaneously considered for the study of the physical phenomena related to the use of jet-grouting treatments in geotechnical engineering. After the first phase of injection, the mixture of remoulded soil, cement, water and additives that is left undergoes a highly exothermic process of setting during which the hydration reactions of the cement take place. Such reactions generate fully coupled thermo-hydro-chemo-mechanical (THMC) interactions within the jet-grouted soil (JGS) and the surrounding soil (SS), including changes in the viscosity and the density of water and air, dependence of the curing process on the temperature history, thermally induced chemical reactions within the SS and variations of the stiffness and strength of the JGS and the SS.

The mechanical behaviour of the JGS and the time variation of its constitutive parameters have been observed to depend on the type and content of cement and additives, the water/cement ratio, the curing time, the curing temperature, the type of SS and its initial stress state –depth- or the initial pH value. There is also experimental evidence that the yield locus of soils reduces as temperature grows, which implies that the release of hydration heat and its transmission through the SS may induce settlements close to the treated zone in normally consolidated soils.

The complexity of this kind of problems is, hence, remarkable. In this work we describe a theoretical framework that may be employed for the analysis of geotechnical problems involving jet-grouting treatments. We also present and discuss the results of some numerical experiments that illustrate the performance of the proposed model.

2 A FRAMEWORK FOR THE STUDY OF THE THMC PHENOMENA ASSOCIATED WITH JET-GROUTING

2.1 Basic hypotheses

Due to the great complexity of the problem, some simplifying hypotheses are needed to obtain operative models. At this stage, the developed framework is based on the following assumptions:

(i) The surrounding soils are saturated; Terzagui's effective stress principle holds for these materials.
(ii) No chemical processes take place within the SS; only THM couplings are considered in the surroundings of the treated zone.
(iii) The installation of the JGS is simulated by substituting zones of SS by zones of fresh JGS in a FEM mesh. The erosion caused by the injection process and its possible effects on the stress states of the surrounding soils are not taken into account.
(iv) From the moment of its placement, the JGS is impermeable compared with the SS.
(v) Only elastic strains, thermal reversible strains, shrinkage strains and plastic strains are considered; creep strains are not included in the analyses.
(vi) The behaviour of the JGS is always perfectly plastic and it depends on total stresses.

2.2 Governing equations and boundary conditions of the problem

The basic hypotheses described above may be combined to obtain the equations that control the evolution of the state variables of the JGS and the SS [1-4], that is: balance of momentum, balance of energy, balance of water mass –the equation of balance of solid mass is incorporated within the others-. In particular, the equations of equilibrium of stresses are written in weak incremental form and, under plastic loading, the increment of stresses depends, in addition to the classical elastoplastic matrix, on the derivative of the yield function with respect to the temperature -SS- or with respect to the *degree of hydration* –JGS, see below-.

As for the JGS, despite working in terms of total stresses and assuming the material to be impervious, an auxiliary equation of balance of water mass imposing null water flux is also introduced for the sake of the simplicity of the implementation. The inclusion of such equation in the formulation produces values for the water pressures in the interior of the JGS; such pressures have no physical meaning.

On the other hand, the possibility of appearance of fresh JGS zones at any time requires introducing some special conditions in the formulation. In particular, the changes in the specific weight of the material must be equilibrated before continuing the computations, and the temperature of the JGS at the moment of its placement must be imposed by the user, except at nodes where the general boundary thermal conditions are prescribed.

2.3 Release of hydration heat and mechanical response of the JGS and the SS

To complete the framework it is necessary to introduce in the governing balance equations some specific constitutive models for the release of heat and for the mechanical behavior of the JGS and the SS including the MC effects of the hydration reaction within the JGS and the THM effects of the associated heat release within the SS-. In [4,5] a detailed description of the models employed may be found, as well as a discussion on their agreement with the available experimental results; a summarized depiction of their main features is as follows:

i) The release of hydration heat is proportional to the rate of change of the degree of hydration, ξ, defined as the mass of hydrates formed by unit volume divided by the respective mass at the end of the hydration process [6]. This rate of change may be assumed to depend on the in situ curing temperature according to a Arrhenius-type law:

$$\dot{\xi} = \tilde{A}(\xi)\exp\left(-\frac{E_a}{RT}\right),\ \tilde{A}(\xi) = B_2\tilde{A}_0(\xi) + B_1 - \left[B_1 + \tilde{A}_0(1)B_2\right]\xi,\ \tilde{A}_0(\xi) = a\frac{1-e^{-b\xi}}{1+c\xi^d} \qquad (1)$$

ii) As a first approximation, the JGS is modelled as a Mohr-Coulomb material with perfect plasticity and isotropic elasticity whose constitutive parameters depend only on the hydration ratio and the load history. In particular: a) the strength and stiffness properties of the JGS are strongly linked to the release of heat due to the hydration reactions that take place within the jet-grouted mass [7,8]. The behaviour of the material is almost that of a fluid for degrees of hydration lesser than 0.5; from larger values, the Young modulus and the compressive strength grow almost linearly with the hydration degree, b)the technique presented in [9] is applied to smooth the Mohr-Coulomb yield surface; the application of the smoothing procedure introduces an auxiliary parameter in the formulation, which allows us to control the tensile strength independently of the compressive strength and c) the ratio of stiffness and strength increase with the degree of hydration may be reduced or zeroed if a point of the JGS undergoes plastic strains beyond a certain threshold. Other similar loading-dependent conditions may be likewise imposed.

iii) The basic model designed for the SS includes: a) Elastic bulk modulus proportional to the effective mean stress, b) a Mohr-Coulomb type shear failure envelope; this failure mechanism is assumed to be perfectly plastic, c) a volumetric hardening cap depending on the preconsolidation pressure, which is assumed to be controlled by temperature; a thermo-plastic parameter is introduced according to [10,11] so that thermally-induced volumetric plastic strains are associated to movements of the cap., and d) the technique presented in [9] is used to obtain a smooth model incorporating the two plastic mechanisms outlined above.

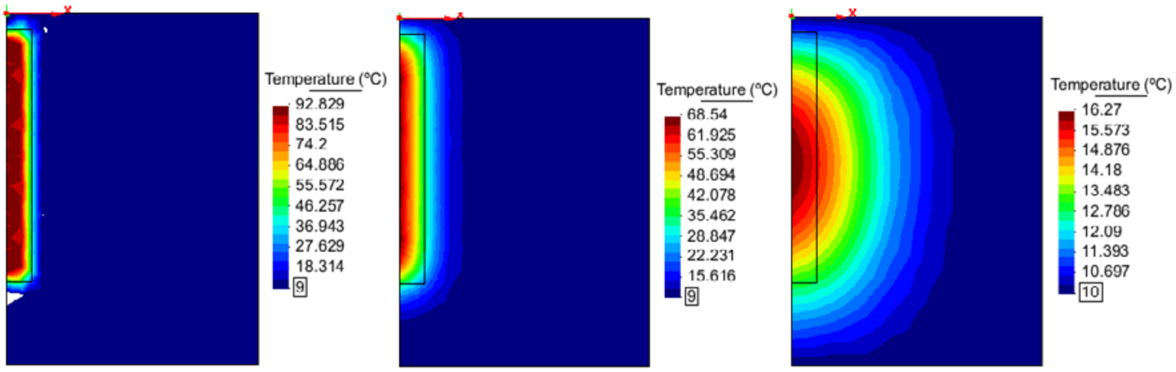
3 APPLICATION

The balance equations and models described in the previous Section have been implemented within a FEM code based on CODE-BRIGTH, a program developed for the modelling and analysis of coupled THMC interactions in geotechnical problems [2].

The analysis case chosen for presentation here is that of a single jet-grout column constructed within a thermo-plastic soil. For a better understanding of the effects of the volumetric thermo-plastic mechanism of the SS, we may perform a simulation by neglecting thermal reversible strains in the JGS and in the solid particles of the SS and shrinkage strains in the JGS. The studied geometry -2D axisymmetric model- consists in a 15 meter-long vertical column with a 3 meter diameter; it is assumed that the construction of the column takes 3 hours. The thermo-plastic parameter for the SS was obtained by adjusting the experimental results reported in [10] for samples of saturated Boom clay. As for the JGS, the latent heat of hydration has been computed according to [6] and assuming 400 kg of cement per m^3 of column (a moderate value of the cement content in high-diameter columns). The initial stress state was generated by applying the K_0 method with $K_0 = 1 - \sin\varphi$ and considering hydrostatic water pressures with the water table at the soil surface. After that, a phase of stress adjusting is performed (from t=0 to t=1 h); at t=1 h, the SS mass is normally consolidated with initial temperature 10ºC and initial porosity 0.3. The initial temperature of the JGS is assumed to be $15^{\circ} C$.

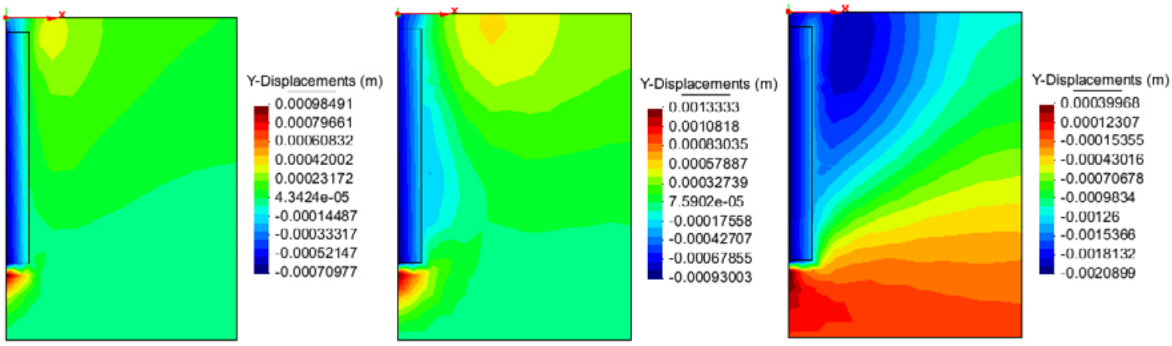
Results in terms of contours at three different tomes are shown in Figures 1, 2 and 3 that show temperatures and vertical displacements, respectively. Vectors of water flux at the same times are depicted in Figure 3. The evolutions of the degree of hydration and of the Young's modulus in the centre of the column are shown in Figure 4.

As a consequence of cement hydration (an exothermic reaction), temperatures increase. The evolutions of temperature at two different points are presented in Figure 5a; it can be observed that in the center of the column, temperatures close to 100ºC are achieved. Associated surface settlements at different points are plotted in Figure 5b.



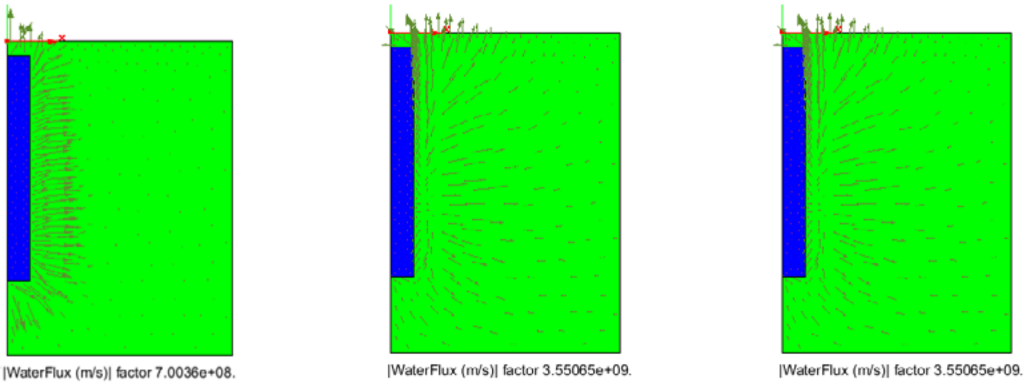
a) b) c)

Figure 1: Contours of temperature at different times. a) 50 hours, b) 500 hours, c) 5000hours



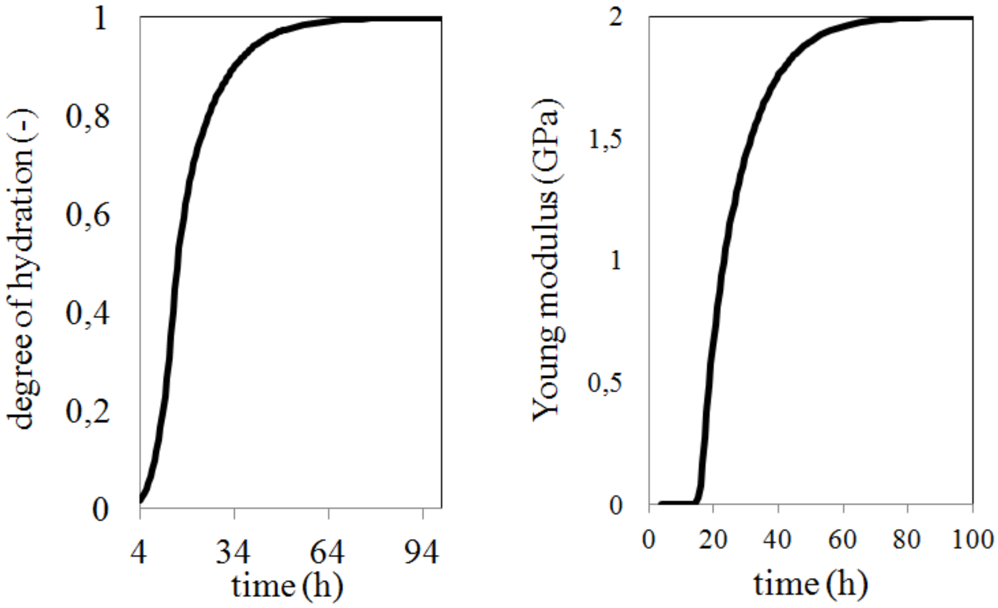
a) b) c)

Figure 2: Contours of vertical displacements at different times. a) 50 hours, b) 500 hours, c) 5000hours



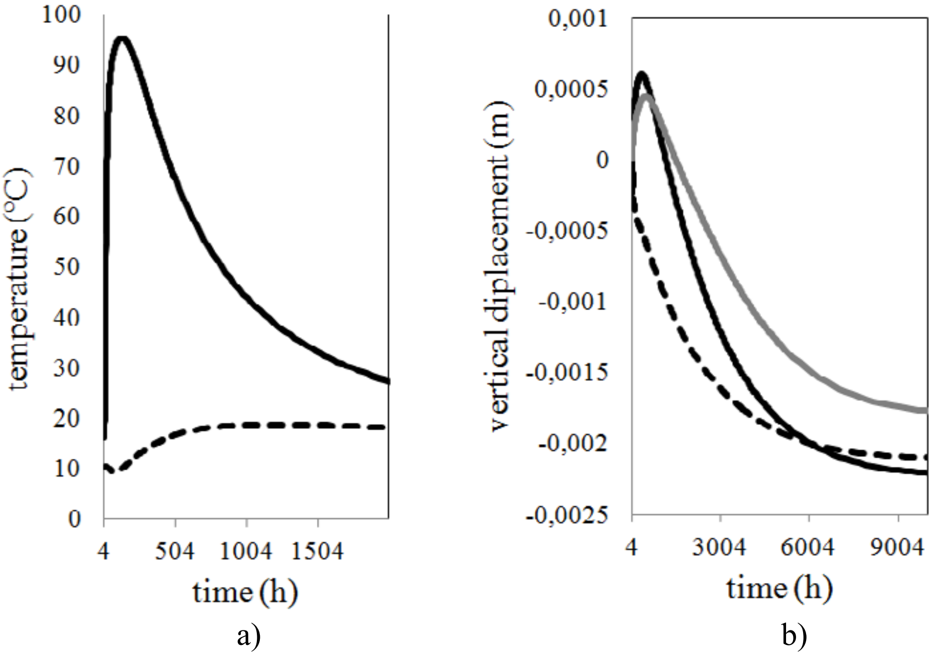
a) b) c)

Figure 3: Flux vectors at different times. a) 50 hours, b) 500 hours, c) 5000hours



a) b)

Figure 4: a) Evolution of the degree of hydration in the centre of the column. b) Evolution of Young's modulus in the centre of the column



a) b)

Figure 5: a) temperature at a point in the center of the column (solid) and at a point of the SS three meter away from the axis (dashed) –both points are at a depth of approx. 8.5 m, b) settlement for a surface point five meter away from the axis (black solid), ten meters away from the axis (grey solid) and on the axis (black dashed)

4 CONCLUDING REMARKS

A framework for the study of the coupled THMC interactions associated to the use of the jet-grouting technique has been summarily described. The developed framework has been implemented within a FEM program, which is being used to analyze effects that are not clearly covered by the current design practice for jet-grouting treatments, mostly based on empirical rules. A better understanding of such effects would lead to a more rational use of this soil improvement technique.

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