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TRIAXIAL TESTS ON FROZEN GROUND: FORMULATION AND MODELLING

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Abstract. Artificial Ground Freezing (AGF) is a controllable process that can be used by engineers to stabilise temporarily the ground, provide structural support and/or exclude groundwater from an excavation until construction of the final lining provides permanent stability and water tightness. In this work, the process of ground freezing is studied using a constitutive model that encompasses frozen and unfrozen behaviour within a unified effective-stress-based framework and employs a combination of ice pressure, liquid water pressure and total stress as state variables. The parameters of the constitutive model are calibrated against experimental data obtained from samples retrieved during construction of Napoli underground, in which AGF was extensively used to excavate in granular soils and weak fractured rock below the ground water table.

1 INTRODUCTION

Frozen ground is soil or rock with a temperature below 0°C. The thermo-hydro-mechanical processes induced by freezing and thawing of pore fluid within soils are complex and can have significant mutual geotechnical interaction [1]. As the temperature decreases the ice content increases and the ice becomes a bonding agent between soil particles or blocks of rock increasing the strength of the soil/rock mass and modifying the pore water pressures and the effective stress on the soil skeleton, which, in turn, induces mechanical deformation. At the same time, any changes in the hydraulic and mechanical boundary conditions can affect the thermal processes by advection and changes of ice and water contents [2].

Artificial Ground Freezing (AGF) is a controllable process and can be used profitably by civil and mining engineers to temporarily provide structural support and/or to exclude groundwater from an excavation until construction of the final lining provides permanent safety. The process was originally applied mainly to vertical openings, such as shafts or pits, but, with the increasing ability to drill and install freezing tubes horizontally, other excavation works, such as tunnels, were considered. Besides protecting excavations, AGF has also been used to stabilize slopes, to sample coarse grained soil, to construct temporary access roads, and to maintain permafrost below overhead pipeline foundations and below heated buildings.

AGF is one of the construction techniques that were extensively adopted during construction of Line 1 of Napoli Underground, to ensure stability and waterproofing of the platform tunnels and inclined passageways during excavation below the ground water table through loose granular soils of pyroclastic origin, Pozzolana, and a fractured soft rock, Neapolitan Yellow Tuff [3-5].

This paper presents the first results obtained using a fully thermo-hydro-mechanical (THM) model [1], calibrated against experimental data obtained under temperature controlled conditions on Pozzolanas retrieved from the subsoil in Municipio Station. The testing programme was carried out by Tecno-in SpA (www.tecnoin.it/en) as part of the geotechnical investigation for the works of Napoli underground. The analyses have been carried out using the code CODE_BRIGHT [6], the formulation and thermo-hydro-mechanical constitutive laws used are described in detail in [1,2]. In particular, the mechanical model uses an elastoplastic constitutive law based on the Barcelona Basic Model (BBM), taking advantages of the close analogy between unsaturated soils and frozen soils [2].

2 EXPERIMENTAL RESULTS

The tests were performed using a double walled triaxial cell originally developed by Tecno-in SpA which works under temperature controlled conditions, see Figure 1.

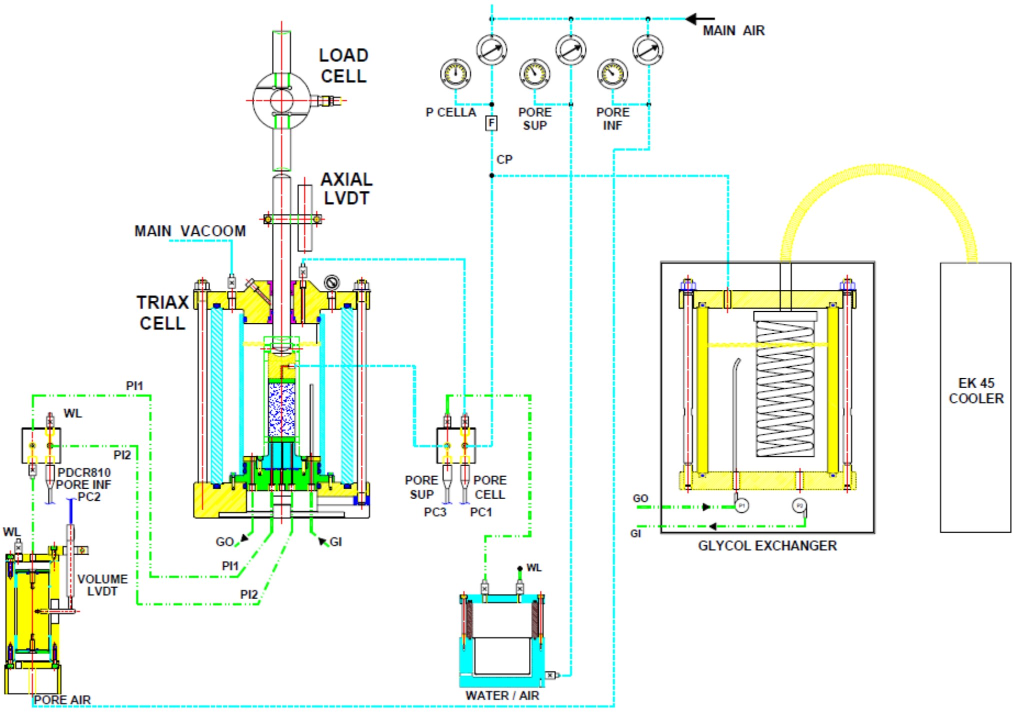


Figure 1: Experimental layout [7]

The cell fluid (glycol), acts also as the refrigerating medium and is circulated in an inner cylinder containing the sample, while the outer cylinder is kept under vacuum to limit condensation. The loading ram moves vertically in a sleeve seal, which is connected to an LVDT for the measurement of vertical displacements. The axial load is measured using an external load cell fixed under the cross bar of the loading frame. Tests are generally performed at controlled displacement rate. There are three independent pressure circuits, one controlling the cell pressure and two controlling the pore water pressure in the sample. A probe placed in the middle of the samples monitors its temperature. Further details on the experimental set-up are given in [8].

The laboratory tests were performed to characterise the mechanical behaviour of the natural soils at low temperatures. Undisturbed samples were retrieved from the site of Muncipio station at different depths, for a total of 10 samples in the granular deposits (Pozzolanas) and 9 samples from the underlying soft rock (Neapolitan Yellow Tuff). The tests included unconfined and triaxial compression tests and indirect extension tests on unfrozen, frozen and frozen/unfrozen samples. Figure 2 shows the stress paths followed by three samples of Pozzolana in the p:T and p:q planes.

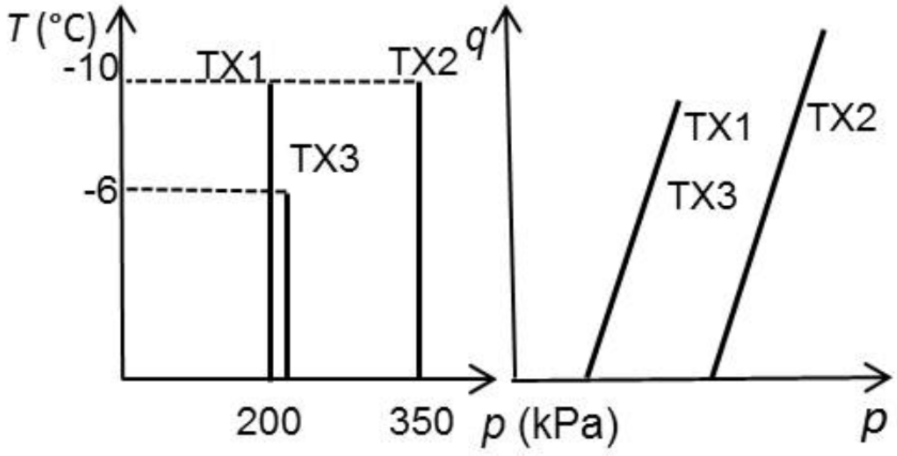
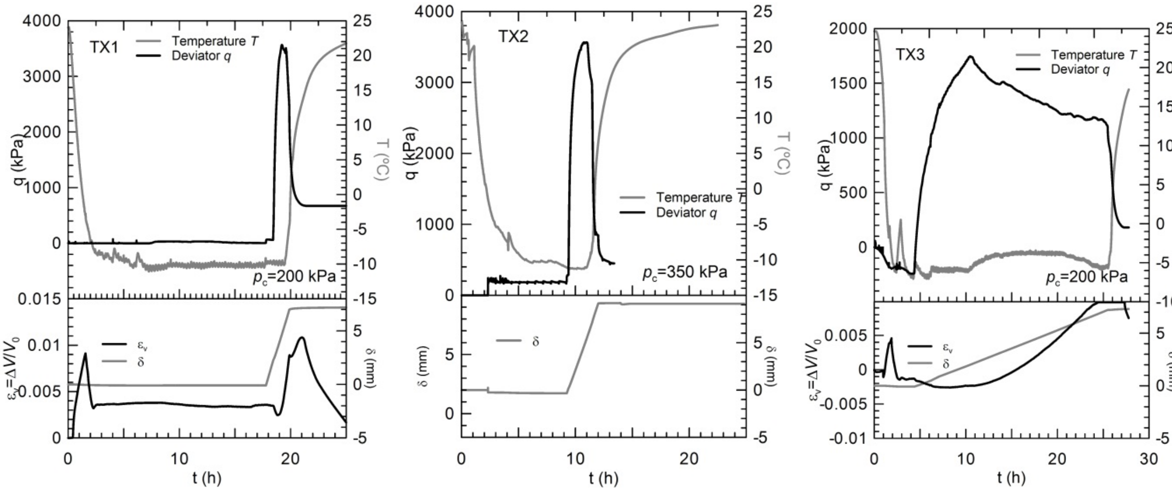


Figure 2: Stress path followed by three samples in the *p-T* and *p-q* plane

The main phases of the tests are: i) drained isotropic compression to mean total stress p = 200 ÷ 350 kPa, ii) freezing to temperatures T = -5 ÷ -10 °C over a time of about five hours followed by an equalization stage at constant temperature, iii) axial loading at controlled displacement rate of 10-6 mm/s for tests TX1 and TX2 and 10-7 mm/s for test TX3, and iv) thawing after axial loading under maintained displacement. Figure 3 reports the results of the three tests in terms of deviatoric stress, q, volumetric strain, ε_v, temperature, T, and axial displacement, δ, as a function of time, t.

The volume strain recorded during all tests indicates a tendency for the sample to increase its volume during the initial part of the freezing stage. This is followed by an apparent decrease of the volume strain before reaching an approximately constant value during equalisation. It must be noted, however, that the water in the drainage circuit freezes and so the external measurements of volume strain are not reliable below 0 °C. Different methods to measure the volume strain of the sample are being developed to overcome this problem.



a) b) c)

Figure 3: Experimental results: (a) Test TX1, (b) Test TX2, and (c) Test TX3

The shearing stage of test TX3 was carried out at a temperature ranging between -6 and -4°C, see Figure 4(c). In this case, the peak deviatoric stress, obtained for $\delta = 2$ mm and at a temperature $T = -6$ °C, was $q_p = 1740$ kPa, after which the temperature increased up to -4°C and the deviatoric stress decreased to 1200 kPa. During the shearing stage the external system for volume strain measurements records a small contraction of the sample followed by dilation as the peak deviatoric stress is attained. For the reasons outlined above, however, the reliability of these measurements of volume strain is questionable.

Axisymmetric coupled THM analyses were performed to validate the constitutive model under different temperatures and mean confinement stress. A step of 24 hour of linearly decreasing temperature to $T = -5$ or -10º C was applied to the external boundaries of the mesh, both allowed movement during freezing. The initial pore water pressure in the sample at the beginning of freezing was set to zero, and external boundaries of the mesh were drained. Axial loading was carried out prescribing a constant rate of vertical displacement to the top boundary of the mesh.

3 MODELLING RESULTS

The parameters defining the freezing retention model and the loading collapse curve were calibrated using literature data obtained in [9,10] on Pozzolanas similar to those under examination although retrieved from different sites. Parameters M and G were obtained by back-analysis of the behaviour of unfrozen samples reported in [8], while the remaining parameters were calibrated against the experimental results reported herein.

Figure 4 shows the contours of temperature, T (°C), liquid water pressure, P_l (MPa), porosity, n, and equivalent degree of saturation S_{eq} ($=S_l+(\rho_{iw}/\rho_{lw})S_i$) at a specific time ($t = 14$h) for the simulation of the freezing stage of test TX3. The model reproduces correctly the advancement of the freezing front from the boundary of the sample towards its centre, with a gradient $\Delta T/\Delta r \approx -1.2/0.019$ (º/m), see Figure 4a. Due to the decreasing temperature, the liquid water pressure becomes negative where the freezing front advances, see Figure 4b.

Also, in the frozen area, there is a marked increase of porosity induced by phase transformation (from water to ice) coupled with the changes of liquid water pressure, see Figure 4c, and a corresponding decrease of liquid water saturation, see Figure 4d.

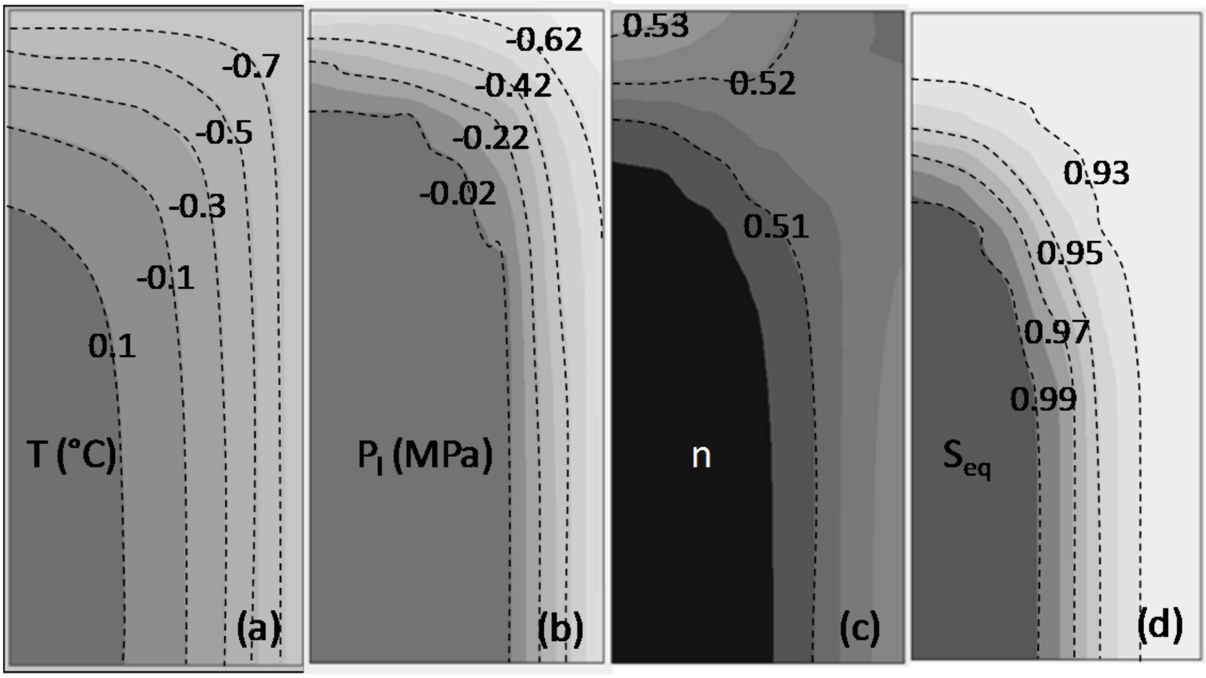


Figure 4: Test TX3 - Results of numerical simulations: freezing stage. a) temperature *(T)*, b) liquid water pressure (P_l), c) porosity (*n*), d) liquid water saturation (S_{eq})

Figure 5 shows the deviatoric stress versus axial strain curves obtained from the numerical simulation of the shearing stage of all three tests, together with the experimental results. Consistently with the experimental conditions, the imposed displacement rate in the simulation of test TX3 was one order of magnitude less than that adopted in the simulation of tests TX1 and TX2. Also, the values of the initial unfrozen over consolidation mean effective stress in the numerical simulation of the tests on different samples were not the same (p'_c=400 kPa for samples TX1 and TX3, and p'_c=330 kPa for sample TX2). This is due to the different depth of retrieval of the different samples.

The agreement between model predictions and experimental data is very satisfactory both for the samples tested at the same temperature with two different confining stress (TX1 and TX2) and for those tested at the same confining stress at two different temperatures (TX2 and TX3).

The final thawing stage under maintained displacements was also simulated numerically for all tests. Figure 6 shows the computed contours of temperature, *T* (°C), liquid water pressure, P_l (MPa), and equivalent degree of saturation, S_{eq}, at a specific time in the simulation of the thawing stage for test TX3. The model correctly reproduces the advancement of the thawing front from the boundary of the sample to its centre with a gradient $\Delta T/\Delta r \approx 0.01/0.19$ (°/m). Due to the increasing temperature, the liquid pressure increases as the thawing front advances. The liquid water pressure is higher in the upper part of the sample due to the axial load transmitted by the top platen.

In this step of increasing temperature (ε_a>0.03) the model reproduces quite well the observed behaviour during axial loading.

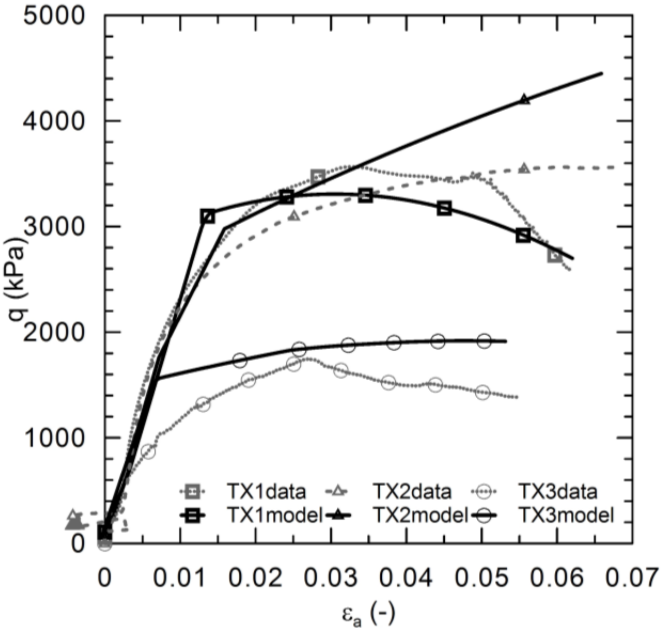


Figure 5: Measured and predicted stress strain behaviour in triaxial compression. Tests TX1, YTX2 and TX3

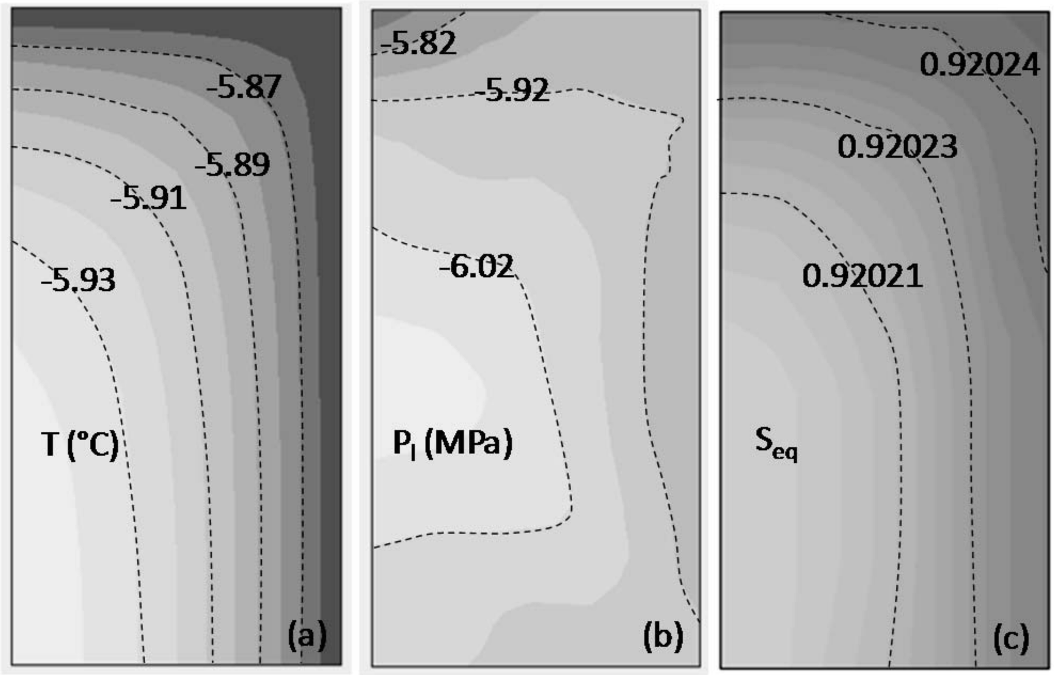


Figure 6: Test TX3 - Results of numerical simulations: thawing stage. a) temperature *(T)*, b) liquid water pressure (P_l), c) liquid water saturation (S_{eq})

4 CONCLUDING REMARKS

This paper has illustrated the first results of a research into the fundamentals of frozen soil behaviour, bringing together constitutive modelling, laboratory tests and field data. A fully coupled thermo-hydraulic-mechanical model extended to low temperature problems has been validated in freezing and thawing against experimental data obtained in triaxial compression at different temperatures and confinement pressures. The mechanical behaviour of the frozen soil has been modelled by an elastoplastic constitutive law based on the BBM. The performance of the model is satisfactory during all stages of the test, including drained compression, freezing, equalisation, axial loading in frozen conditions, and thawing.

Further work, currently under way, includes modifications to the temperature controlled triaxial equipment to measure volume strains of frozen soil and change the freezing mechanism such that the freezing front will proceed from the centre of the sample towards its boundaries, with an effect on the hydraulic boundary conditions. From the point of view of constitutive modelling modifications to the present formulation are being examined to include the viscous behaviour of the ice phase, mechanical degradation on cycles of freezing and thawing, and the adoption of the Bishop average stress as a constitutive variable.

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