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Analytical and Numerical Studies on the Behavior of a Freezing Soil Layer

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Abstract : The target of this paper is to investigate how saturated poroelastic soils subject to freezing temperatures behave and how different boundary conditions can intervene and affect the thermo-hydro-mechanical (THM) responses, based on a particular but classical configuration of a finite homogeneous soil layer studied by Terzaghi. The essential relations on the constitutive behavior of a freezing soil are firstly recalled: ice crystal - liquid water thermodynamic equilibrium, hydromechanical constitutive equations, momentum balance, water mass balance, and the thermal diffusion equation, in general, non-linear case where material parameters are state-dependent. The system of equations is firstly linearized, assuming all material parameters to be constants, particularly the permeability of liquid water, which should depend on the ice content. Two analytical solutions solved by the classic Laplace transform are then developed, accounting for two different sets of boundary conditions. Afterward, the general non-linear equations with state-dependent parameters are solved using a commercial code COMSOL based on finite elements method to obtain numerical results. The validity of this numerical modeling is partially verified using the analytical solution in the limiting case of state-independent parameters. Comparison between the results given by the linearized analytical solutions and the non-linear numerical model reveals that the above-mentioned linear computation will always underestimate the liquid pore pressure and displacement, whatever the hydraulic boundary conditions are. In the nonlinear model, the faster growth of ice crystals, accompanying the subsequent reduction of permeability of freezing soil layer, makes a longer duration for the depressurization of water liquid and slower settlement in the case where the ground surface is swiftly covered by a thin layer of ice, as well as a bigger global liquid pressure and swelling in the case of the impermeable ground surface. Nonetheless, the analytical solutions based on linearized equations give a correct order-of-magnitude estimate, especially at moderate temperature variations, and remain a useful tool for preliminary design checks.

Keywords : chemical potential, cryosuction, Laplace transform, multiphysics coupling, phase transformation, thermodynamic equilibrium
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