Conclusions

7.1 Summary and concluding remarks

7.1.1 Three-phase FE model within thermoporoelasticity

A three-phase FE model for freezing soils consisting of solid grains, pore water and pore ice was presented for the description of the coupled THM behavior of water-saturated soft soils subjected to frost action. A basic model was first formulated within the frameworks of thermo-poroelasticity (COUSSEY 2005) and premelting dynamics (WETTLAUFER AND WORSTER 2006) (see also MESCHKE ET AL. (2011), ZHOU AND MESCHKE (2011a,b, 2012, 2013)). By choosing solid displacement \( u \), the liquid water pressure \( p_L \) and the temperature \( T \) of the mixture as primary field variables, three corresponding physical laws were set up as the governing balance equations for the FE formulation as an IBVP, within which the interaction terms represent the related THM couplings. It was demonstrated by three validation tests in Section 2.5, that the basic model is capable to reproduce the fundamental interacting mechanisms occurring during the freezing process, such as the phase transition and associated latent heat effect, the liquid transport within the pores and associated mechanical deformation of the solid skeleton. Additionally, the contribution of the micro-cryo-suction mechanism to the frost heave phenomenon was included, whereas most recent studies consider only the contribution due to the volume expansion of water transforming into ice. However, with an assumption of nondissipative phase transition, the capillary hysteresis observed during freeze-thaw cycles was not incorporated.

7.1.2 Strength homogenization of matrix-inclusion composites

For the prediction of the temperature- and porosity-dependent strength properties of freezing soils, a novel multi-scale strength homogenization procedure has been proposed. As a reference scheme for each step, a robust strength homogenization methodology for a two-phase nonlinear matrix-inclusion composite was first presented by extending the LCC approach proposed by ORTEGA ET AL. (2011) within the yield design framework SALENCON (1990). The presented reference
scheme allows for predictions of the homogenized strength properties of composite materials for different assumptions concerning the individual strength properties of the cohesive-frictional matrix material and the inclusions. The matrix material may be either represented by a Drucker-Prager-type (hyperbolic) or an elliptical strength criterion, which are typically adopted for geological and cement-based materials. As the inclusion phase either air voids, representing a composite with air pores, pores filled with a fluid, representing a water-saturated porous composite, cohesive-frictional materials of the same type as the matrix phase, but with different strength properties, representing a composite reinforced by aggregates, are considered. In addition, as a limit case, also composites reinforced by rigid inclusions are considered. The LCC methodology predicts the macroscopic strength of a nonlinear composite by means of determining the dissipation potential from an optimally chosen linear thermo-elastic comparison composite with a similar underlying microstructure, which is used to evaluate limit states of macroscopic stresses in the framework of the yield design theory. An efficient algorithm was proposed to generate the macroscopic dissipation potential, which allows to establish the macroscopic strength functional in terms of stress invariants in an explicit format for all investigated cases, including complex combinations of matrix and inclusions characterized by Drucker-Prager-type as well by elliptic strength criteria. The generated strength criteria are also of a hyperbolic or elliptical format. This analytical format allows a straightforward generalization of the proposed procedure to a multi-scale strength homogenization strategy for complex hierarchical composites.

This reference strength homogenization scheme has been applied to different classes of composites (see also Zhou and Meschke (2014b)). The numerical applications have shown, that the generated strength envelopes of the composite material correctly predicts the limit cases with regards to volume fractions of the inclusions at \( n = 0 \) and \( n = 1 \). A Drucker-Prager-type matrix with air voids yields a strength criterion which shows a transition from a hyperbolic to an elliptic characteristics with increasing volume fraction, finally collapsing to a point as \( n \to 1 \). A matrix with an elliptic strength criterion with air voids leads to an elliptical macroscopic strength envelope which shrinks with increasing void ratio and also degenerates to a point as \( n \to 1 \). Composites with a matrix material and solid inclusions both being characterized by either a hyperbolic (Drucker-Prager-type) or a elliptic criterion (i.e. a criterion, which predicts strength limit in both hydrostatic tension and compression) show, at a macroscopic level, a smooth transition between the strength envelopes of both phases. The model predictions for selected classes of composites were compared with results from a 1-D thought model (Dormieux et al. 2006), experiments on sand specimens with gravel inclusions (Pedro 2004) and on leached and unleached cement specimens (Heukamp et al. 2003, Lemarchand et al. 2002), respectively, as well as with an alternative strength homogenization method – the modified secant model (Magnous et al. 2009). A very good correlation between model predictions for the homogenized strengths characteristics for unleached and leached mortar was obtained. However, a considerable overprediction of the friction coefficient were found for the upscaling of composites reinforced with rigid inclusions. It should be noted, however, that in contrast to the modified secant model by Magnous et al. (2009), the proposed model predicts the correct asymptotic limit for the friction coefficient \((M \to \infty)\) as \( n \to 1 \). This overprediction of the friction coefficient is attributed partially to the fact, that, as a consequence of
the principle of maximum plastic dissipation inherent to the upper bound theorem within the yield design theory, the LCC-based upscaling method is not able to capture non-associated plastic flow observed for many geological materials. In addition, it is concluded from the comparison with the modified secant model proposed by Maghous et al. (2009), that the differences may also arise from the linear averaging rule applied for the definition of the effective strain rate in the proposed model.

7.1.3 Strength upscaling for freezing soils

On the basis of the validated reference scheme, in the proposed two-step strength upscaling strategies, the solid particle phase and the crystal ice phase are assumed to be characterized by two different Drucker-Prager strength criteria and the liquid water phase has, either zero strength capacity under drained condition, or zero shear strength capacity under undrained condition. Through the first homogenization step, the influence of porosity on the predicted strength properties for fully frozen soil has shown qualitatively a good correlation with the test results reported by Kaplar (1971), where a cohesion larger than that of pure ice was obtained due to the synergistic strengthening between the solid grains and ice matrix, and gradual establishment of particle contact. In the second homogenization step for drained freezing soil, the predicted strength criterion would undergo a transition from hyperbolic (or Drucker-Prager-type) to elliptic for large liquid volume fraction, due to the void weakening, whereas for undrained freezing soil, it remains always hyperbolic (or Drucker-Prager-type) without hydrostatic strength limit in compression. In the complementary step for the undrained case, consideration of the ice pressure melting effect leads to good concordance between the strength prediction of the ice-water mixture with appropriate-chosen $\Delta T_{ch}$ and $m$, and the experimental data on ice strength collected by Fish and Zaretsky (1997).

Through model evaluation at the end of each homogenization step, the resultant strength prediction for the failure criterion of ice-water mixture is in excellent concordance with the experimental data provided two appropriate-chosen parameters that characterize the pore size and pore size distribution, while the prediction for undrained partially frozen soil shows qualitatively a good agreement with observed phenomena, such as strengthening of soil during freezing and weakening of soil during pressure melting. Moreover, the proposed strength upscaling strategies are validated further by comparing the predicted strength properties systematically with experimental results on fully and partially frozen Ottawa sand presented in Alkire and Andersland (1973), Baker (1979), Goughnour and Andersland (1968), through which the dependencies of macroscopic strength properties of freezing soils on porosity and liquid saturation degree have been nicely represented, such as synergistic strengthening effects between the sand particle and crystal ice observed in sand-ice composites, and the frictional resistance depression due to the presence of ice by interfering with the inter-granular contact between sand particles.

7.1.4 Critical state elastoplastic mechanical constitutive model

Subsequently, the framework was extended from poroelasticity to poroplasticity and accordingly a new critical state elastoplastic mechanical constitutive model has been proposed, by adopting the
CASM for the reference unfrozen state, and successfully extending it to freezing states based on
the concepts of the enhanced BBM. As a highlight of this thesis, the temperature- and porosity-
dependent strength properties of freezing soils predicted through the two-step strength upscaling
procedure were incorporated into the constitutive model. The verification of the algorithmic for-
mulation and evaluation of the proposed constitutive model were conducted by four benchmark
examples in both unfrozen and freezing states. By means of an isotropic compression test and two
triaxial compression tests on unfrozen soils at different OCRs, important features observed in real
soils (Wood 1990) have been predicted, such as plastic hardening followed by volumetric con-
traction for lightly overconsolidated soil, plastic softening followed by volumetric contraction for
heavily overconsolidated soil, and infinite plastic shearing occurring without any volume change in
the critical state. In the freezing tests, the dependence of shear strength on temperature has been
demonstrated, together with the expansion of yield surfaces in both compressive and tensile direc-
tions due to, respectively, particle interlocking and ice strengthening.

7.1.5 Simulation examples

In the one-dimensional soil freezing test dealing with the development of ground freezing, the cryo-
suction process, identified as the driving force of the frost heave phenomenon (Taber 1929, Zhu
et al. 2000), has been successfully represented with a continuous but slowed-down ice accumu-
lation in the frozen fringe. This frost accretion initiates an ice lens formation, however, with as-
sumptions of a purely temperature-dependent liquid saturation and a zero ice flow, the formation of
ice lens or alternating layers of ice lenses can not be reproduced in the present work. Through a
comparison study on four tests, it has been concluded that the latent heat released during freezing
process is an essential prerequisite for the observed frost accretion, whereas the volume expansion,
resulting from the density difference between water and ice, turns out to be relatively insignificant.
Besides, drainage in the unfrozen zone provides a continuous external water supply for the ongoing
frost accretion, whereas in an undrained system frost accretion occurs as well however with less
heave.

In the application example concerned with AGF to provide temporary excavation support, it was
shown, that the volume expansion due to phase transition and the cryo-suction effect contribute both
to the frost heave observed on the ground surface. Besides, the seepage flow has a considerable
influence on the formation of a closed and stable arch of frozen ground. The comparative study on
the optimization of the freeze pipe arrangements indicates that a flow-adapted arrangement of the
freeze pipes can result in a significant shorter time for the freezing process. For a project-specific
freezing system provided the actual groundwater conditions at the tunnel site, the operating costs
can be significantly reduced by investigating an optimized arrangements of freeze pipes.

7.2 Outlook

Although the presented three FE model of freezing soils is already capable of reproducing the cou-
pled THM behavior involved in the ground freezing during tunnel construction for excavation sup-
In reality, during freeze-thaw cycles hysteresis effect exits due to dissipative phase transition and capillary hysteresis. As a result, a hysteresis loop is generally observed in the liquid saturation curve (Fabbri et al. 2009). To take into account this hysteretic nature, the purely temperature-dependent liquid saturation function (2.33) has to be improved by adopting a hysteretic SWCC and considering dissipative phase transition (Pham et al. 2005).

The formation and growth of ice lenses within the frozen fringe are interesting phenomena observed during soil freezing as a result of thermal regelation (see Subsection 2.1.1). As a result of the ice lens growth, the magnitude of the generated heave can be increased to a large extent (Fowler and Krantz 1994) and the resultant lateral nonuniformity can cause massive damage to the surface infrastructure. For an integrated description of the frost heave phenomenon, a nonzero ice flow with respect to the soil skeleton has to be incorporated in a future extension of the model.

In real soils, the unloading and reloading are neither linear nor logarithmically linear as presented in the present model. For a comprehensive description of the elastic volumetric behavior of unfrozen and freezing soils under both tensile and compressive loadings, more sophisticated functions are needed.

Due to the viscoelastic nature of ice and the complex interaction between the soil grains and pore phases (film water and crystal ice), frozen soil exhibits time-dependent behavior such as creep and relaxation. This time-dependency or rate-dependency can lead to a decrease in strength and stiffness from 40% to 60% of their initial values as stated in Schultz et al. (2008). However, in the presented model, the rate-dependency of the constitutive behavior of frozen soils is not considered. A more realistic mechanical prediction requires an extension of the present work from an elasto-plastic to an elastic-viscoplastic constitutive model that is capable of reflecting the highly viscous constitutive behavior of frozen soils (see e.g. Cudmani (2006), Orth (1986)).