Creep of geomaterials - Some finding from the EU project CREEP

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Abstract: This paper gives a summary of some of the main findings of the EU founded project "Creep of geomaterials", CREEP. CREEP was an Industry-Academia Partnerships and Pathways (IAPP) project funded from the 7th Framework Programme (FP7/2007-2013) of the EC under grant agreement PIAG-GA-2011-286397. The project aimed at establishing a consensus in creep modelling within geotechnical engineering. The materials studied were clay, peat and frozen soils (permafrost). Throughout the project, research on material behavior in lab and field studies was combined with numerical studies using existing and newly developed mathematical frameworks. This paper summarizes some of the findings in the project, although the focus is on the developments in the field of soft soils and soft clay in particular. The paper presents a unified enhanced soft clay creep model, which takes into account anisotropy, structure and rate dependency of the material. The performance of the model is demonstrated through analysis of the Murro test embankment. In addition, the paper gives an overview of some characteristics for frozen soil and peat. Some of the considerations regarding e.g. over consolidation ratio for clay with respect to strain rate are very much valid for peat and frozen soil as well.

Keywords: soil, creep, clay, peat, permafrost, deformation

1 Summary of the CREEP Project

The overall objectives of the EU founded project, CREEP, were to formulate, implement and validate novel time dependent material models for geomaterials. The project aimed at establishing a consensus within the geotechnical community in creep modelling. The project was an Industry and Academia Pathways and Partnership project (IAPP). 130 researcher months were either seconded between the institutions involved or recruited to the institutions. The Norwegian University for Science and Technology (NTNU, Norway) led the project. The other partners consisted of the Norwegian Geotechnical Institute (NGI, Norway), Chalmers University of Technology (Sweden), Deltares (The Netherlands), Shanghai Jiao Tong University (SJTU, China) and the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI, China). Through the project, three international workshops and one international conference were organized. These events, together with presentations from the group in other conferences and in several journal publications, gave attention to the topic of creep in geomaterials. In addition, the project arranged two CREEP schools at NTNU. The main idea of the school was to bring knowledge on modelling and understanding creep in geomaterials into the industry and practice.

2 Project Objectives: Modelling and Understanding Creep in Geotechnical Engineering Practice

It is well known that materials in general have rate/time dependencies in their mechanical behavior. The time scale, in which this time dependency is important, is of course different from material to material and the engineering problem at hand. In geotechnical engineering the time scale, in terms of creep/rate dependency in geomaterials, is in the range of some few hours in case of creep failure, or sometimes seconds in case of cyclic loading, to several decades/centuries, in cases where e.g. prediction of long term settlements are needed. The slow time-dependent movement caused by creep of natural geomaterials can potentially cause damages to infrastructure. High maintenance and repair cost and bi-effects like the social economic cost of closing infrastructure makes accurate prediction of potential creep important in design. There is, however, not any consensus in creep modelling within the geotechnical society. The engineers are often not able to produce reliable calculations results for creep deformations. The reasons for this could be lack of proper engineering models, problems with understanding the existing models, problems with lacking parameters for intact soil or a combination of the above. In the creep project, the consortium set out to formulate, implement and validate novel time dependent models for clay, peat and frozen soil that can be used for time dependent analyses in geotechnical engineering problems. One of the questions to be answered in the project was: "Can existing concepts for creep in clay be adopted to peat and frozen soil?"

3 Clay

Volumetric creep in clay is a well-studied phenomenon. Even though some controversy on the topic within the geotechnical society has previously led to some misconceptions, the volumetric creep in clay within a laboratory timeframe is well documented and has a reasonable idealized mathematical description. As shown by Degago et al. (2011) the isotache concept by Šuklje (1957), developed in the framework from other pioneers like Buisman (1936), has proven to be a reasonable approach. In classical geotechnical engineering methods, shear creep is distinguished from volumetric creep, and has normally been described in a similar manner as creep in metals. For shear creep three stages/phases of creep are recognized. These are: (1) Primary creep where rate of shear deformation is reducing with time. In this phase, the shear creep has similar decay as the volumetric creep description in the isotache framework. (2) Secondary creep, where shear deformation rate is almost constant (viscous behavior). (3) Tertiary creep, acceleration of shear deformation followed by creep rupture/failure. Modelling shear creep has often been done based on the over-stress principle from Perzyna (1966) i.e. using an elasto-viscoplastic (EVP) framework. An advanced model should be able to model both volume and shear creep within one formulation. Note that shear creep is implicitly taken care of by the present engineering models for general stress states, as part of the extension from 1D to 3D stress state. However, model calibration is still only based on the 1D the formulation. One key feature, to be able to model both shear and volumetric creep within one framework, is to consider the effect of particle structure on the behavior of clay. As an example Burland (1990) shows how a natural clay loses its structure with deformation. The present research models at SJTU, Chalmers and NTNU have this feature of destructuration built in to them.

From the different partners of the CREEP project, the CREEP-SCLAY1 model (Sivasithamparam et al., 2015), the EVP-SCLAY1S model (Yin & Karstunen, 2011), the ANICREEP model (Yin et al., 2011) and the n-SAC model (Grimstad & Degago, 2010) have been used as a basis for the development of a unified creep model for soft clays. The differences in the above-mentioned models come from the underlying elasto-plastic model, as all essentially have a similar extension for including creep. The underlying model of CREEP-SCLAY1 model is a model with a rotated and distorted ellipsoid as yield surface (i.e. the ACCM surface after Dafalias (1986)). The hardening rules are adopted from Wheeler et al. (2003). The EVP-SCLAY1S and the ANICREEP model has one extra state parameter describing structure with a destructuration rule from Gens and Nova (1993). The n-SAC model is different from the extended “SCLAY1S” models in the flow rule. The n−SAC model uses a non-associated flow rule in a similar manner as the SANICLAY model from (Dafalias et al., 2006). In the EU-CREEP project a unified model for creep in clay was developed. The developed model is a synthesis of the models mentioned above and is to some extent described with more details later in the paper.

4 Frozen Soils

The difference between frozen and unfrozen soil is that part of the water becomes ice. This makes frozen soil a three-phase material in saturated state and four phase in unsaturated state (soil grains, ice, water and gas). In this project, the focus was directed towards saturated frozen soils. Research activities on mechanical behavior of frozen soils, and a good amount of valuable information, is presented in literature (Konrad & Morgenstern, 1981; Nixon, 1991; He et al., 2000; Arenson & Springman, 2005; Lai et al., 2008; Li et al., 2008; Nicolsky et al., 2008; Lai et al., 2009; Nishimura et al., 2009; Thomas et al., 2009; Yang et al., 2010; Yuanming et al., 2010; Zhu et al., 2010; Wang et al., 2014; Xu, 2014; Zhou, 2014; Zhang & Michalowski, 2015). In addition to the above-mentioned works, the existing empirical knowledge has been the most valuable knowledge for cold region engineering and artificial ground freezing. However, there are still many uncertainties and model weaknesses in this field. Engineering designs in these regions requires a deep understanding of the behavior of frozen soils. Simulating engineering problems requires appropriate constitutive models that are able to represent the coupled thermo-hydro-mechanical behavior of the material.

4.1 Mechanical properties of frozen soil

Various physical mechanisms control the mechanical behavior of frozen soils. Ting et al. (1983) classified these mechanisms into three general categories: (1) The pore ice strength, (2) the soil strength, (3) the mechanical interaction between ice and the soil skeleton. To model the mechanical constitutive relationship, a relevant stress measure is necessary in the model. Several different possibilities exists and has been presented in literature.

Nishimura et al. (2009) are among the first researchers to propose a two-stress state variables model for simulating the behavior of frozen soils. By using the net stress, as the excess of total stress over ice pressure, and cryogenic suction as the relevant stress variables. In their model, increase of ice pressure during the freezing period, results in zero or negative values of net mean stress, and is followed by a tensile failure and soil particles segregation. Zhou (2014) proposed another approach in the framework of two-stress state variables, taking the freezing temperature as the second independent variable, rather than suction. Besides, in this model, the dependency of failure criterion on temperature and ice content is obtained by a strength upscaling procedure based on the microstructures of the mixture. Considering the identity of stress measurement and yield mechanism for ice segregation phenomenon, in the model of Zhou (2014) and the one introduced by Nishimura et al. (2009), they share many similarities. One disadvantage is when shearing soil, after it has segregated, the soil will always show dilative behavior. Zhang and Michalowski (2015) employed a definition of effective stress (i.e. total stress minus water pressure) and the pore ice ratio as the independent variables in their proposed constitutive model. In such a model, an effective suction is obtained without direct use of a thermodynamic relationship.

The above principles work best for soil undergoing freezing (increasing ice content). For permafrost, change in ice content due to loading or changing temperature is important as well as change in properties as functions of temperature for the different phases and pressures. Therefore, in the CREEP project, a different approach than the previous studies was chosen. By introducing the solid phase stress, eq. (1), the contribution to the strength and stiffness from the ice phase is included to this stress measure (Ghoreishian Amiri et al., 2016).

$$\boldsymbol{\sigma}^* = \boldsymbol{\sigma} - S_w \cdot p_w \cdot \mathbf{I} \tag{1}$$

Where **σ*** is the solid phase stress tensor, **σ** is the total stress tensor. S_w is water saturation defined as ratio of V_w on V_p (volume of unfrozen water on pore volume), p_w is the water pressure. The pressure difference between water and ice is calculated using the Clausius-Clapeyron equation (Henry, 2000) which is the prerequisite for equilibrium between ice and liquid phases, (Thomas et al., 2009):

$$S = p_i - p_w = -\rho_i l \ln \frac{T}{T_0} \tag{2}$$

where S is the cryogenic suction, p_w and p_i denote the pressure of water and ice phases, respectively, ρ_i is the density of ice, l is the specific latent heat of fusion, T stands for temperature on the thermodynamic scale and T_0 is the freezing/thawing temperature of water/ice at the given pressure. More details on the creep model for permafrost is given in Ghoreishian Amiri et al. (2016) (the article is found in this special issue of the Journal).

5 Peat

Peat is a complex type of geomaterial, consisting of plant fragments and other organic matter in various stages of decomposition, formed in a submerged aqueous environment. It has striking differences in its material properties and characteristics when compared to the mineral soils. Engineering problems involving peat is generally characterized by large deformations, with a significant portion of deformations manifesting due to creep (Kazemian et al., 2011). Note also that it is important that the large deformations are considered in the numerical calculation of a boundary value problem. Peat is, at its extreme, essentially organic fibers and water. Even though it differs significantly from other geomaterials, current practice in modelling is to treat peat, as it was (organic) clay. For one-dimensional deformation, this assumption has so far proven to be reasonable (Long & Boylan, 2013). For a general stress condition this has not yet been shown to be a valid procedure. It is expected that during shearing the orientation and size of the fibers as well as pre-stressing of the fibers play a significant role in the behavior. Peat is also very heterogeneous and this is an important aspect for developing constitutive models for peat. For the purposes of modeling, soil particles are often idealized as solid (without internal voids), incompressible, rigid, and approximately spherical (Taylor, 2012). Peat particles can be significantly larger in their longest dimension than the silty and clayey materials to which they are often compared with, and generally consist of long, elongated, tubular organic fibers that are far less dense than mineral soil particles. The hollow, perforated, organic structure of peat fibers results in a highly compressible and flexible solid phase, whereas mineral soil grains are generally considered as incompressible and rigid. Fibrous peat has much higher natural water contents than those measured in mineral soils (from 300 % to 2000 % in general). This is largely due to the presence of occluded water (i.e. water encapsulated within the fibers themselves) and the relatively low self-weight. An essential criterion for capturing the behavior of peat is the allowance for deformation response of the solid phase due to two types of loading. In isotropic compression, volumetric strain of the fibers should occur due to the expulsion of micropore water; while buckling or stretching of the fiber should occur in response to shearing. The mechanism behind creep in peat has been attributed to the very slow drainage of water from the micropores of the fibers into the macropore network (Berry & Poskitt, 1972). Since this process is flow driven the viscosity of water will be important for the creep rate, as a result creep in peat is highly temperature dependent. This dependency should be accounted for when using laboratory data at different temperatures than the in-situ temperature. To conclude the deformation behavior of peat exhibits highly non-linear strain rate-dependence, and can be captured by developing the material model within a viscoplastic framework in a similar manner as for clay. However, the use of the term pre-consolidation pressure or apparent over consolidation ratio, *OCR*, is not as appropriate as it is for clay. Especially considering that the initial "effective" stresses in peat is typically only some few kPa. Within the creep project three approaches for modelling creep in peat were tried out. 1. Using a clay creep model (den Haan, 2014). 2. Combining a clay model with a fiber overlay model (Teunissen & Zwanenburg, 2015). 3. Hyperplastic framework (Boumezerane et al., 2015). The project demonstrated that the clay creep model was able to model the volumetric creep behavior of peat reasonably well. So when combining this with the fiber overlay model, Teunissen and Zwanenburg (2015) showed that the fibers have significant effect on behavior under shearing and this approach is promising for modelling this effect. The additional added effect from the fibers alone, to the shear strength, is between 6% and 10%. Teunissen and Zwanenburg (2016) gives more details on this model (the article is found within this special issue of the journal). Finally within the hyperplastic framework Boumezerane et al. (2015) introduced the effect of fibers through a fiber tensor, more publications and development within this approach is still ongoing.

6 Creep modelling

All the different models worked with in the CREEP project are following the concept of over-stress method (Perzyna, 1963). This implies that instead of a yield surface one defines a reference (or static) surface. The rate of plastic strains is defined as a distance in stress space to the reference surface. So for all the clay, peat and permafrost creep models an expression of strain rate as a function of a kind of over-consolidation ratio, *OCR*, is used. However, with slightly different definitions, e.g. for the frozen soil model, in unfrozen state, the definition is shared with the clay model, but in frozen state the water saturation and suction is accounted for in the formulation. The clay model is used here as an example of how the formulation works and to demonstrate the influence of the different parameters in the model. For clay, the equation for volumetric creep strain rate as a function of state (stress and other state variables) can be expressed as given in e.g. Grimstad et al. (2015a):

$$\dot{\varepsilon}_v^{vp} = \dot{\varepsilon}_{v,ref}^{vp} \cdot OCR_{ref}^{\ -\beta} \tag{3}$$

Where β is the creep ratio, $\dot{\varepsilon}_{v,ref}^{vp}$ is a reference volumetric creep strain rate corresponding to the state when the reference over-consolidation ratio OCR_{ref} equals one. Typically, the value for β for clay is in the order of 20 to 35, but it can be lower or higher. For peat this ratio is typically 5 to 20, dependent very much on the organic content. This means that with more mineral content one expect normally a higher ratio. For frozen soils the ratio is a function of ice content, temperature and particle size/mineralogy. This means that for soils with high ice content at "warm" temperatures, a relative low ratio, to that of unfrozen, is obtained (e.g. materials with high silt content) and for soils with low ice content at low temperatures (e.g. clay), a high ratio is expected. Values of β higher than 50 is not reasonable and for such materials, an elastoplastic analysis is preferred due to numerical efficiency.

Note that OCR_{ref} (or simply OCR) is not an index property of the material but a state variable defining the strain rate. A proper selection of OCR is important since the initial value for OCR defines the initial strain rate of a material. It is also very important to recognize, that unlike for an elastoplastic analysis (approximated by high value of β), the initial value of OCR becomes very important for cases where the stress state stays below the pre-consolidation stress. This is especially important for two- or three-dimensional problems (e.g. embankments with limited width) and for 1D problems where the load is limited compared to the initial stresses with depth of the clay deposit (i.e. where the stress state at greater depths only have limited increase compared to the initial stress state). A proper determination of the initial strain rate is though difficult since effects like sample disturbance, tests setup and interpretation procedure will influence the interpretation of the *OCR* from laboratory tests. In addition, the linearization in logarithm of strain rate assumed by the model might deviate from reality for the historically long-term creep that the material has previously experienced in geological time. Since *OCR* is not a true material property, other state variables like e.g. a relative void ratio or initial strain rate could easily be used to replace the use of *OCR* in a model and thereby "hide" the inconsistency between lab test and model parameters from the user. This approach is not selected within this work, here the reference from lab is kept and OCR is adjusted according to expected values. The selection is made in accordance with a qualified guess for the initial strain rate. By using, the actual geological age of the material (or the actual present in-situ deformation rate) to check if the selected value for *OCR* (and β) is in a realistic range, one ensures that there will not be unrealistic deformations occurring in the analysis due to an inappropriate initialization.

Normally the β value and $\dot{\varepsilon}^{vp}_{v,ref}$ are not used as the input parameters to a model directly, as the laboratory tests normally used does not directly provide such values. In engineering practice, different parameters are conventionally used. Mesri and Godlewski (1977) defined the well-known C_α/C_c "law". The ratio of C_α/C_c is approximately equal to the inverse of the β value. Alternatively to C_α and C_c (and C_r) the Cam-Clay parameters λ and κ and creep parameter μ can be used in the model (or in term of strain rather than void ratio λ^* and κ^* and creep parameter μ^*). Again an important note should be taken to the interpretation of C_α or its equivalents ($C_{\alpha\varepsilon}\cdot(1+e_0)$, $\mu\cdot\ln(10)$, $\mu^*\cdot(1+e_0)\cdot\ln(10)$, $r_s^{-1}\cdot(1+e_0)\cdot\ln(10)$ etc.). In conventional practice many of these values are determined from $\log(t)$ plots [where t is time]. As pointed out by Grimstad et al. (2015b) $\log(t)$ is not an objective variable (depends on when time "starts") and will lead to interpretation errors (i.e. under-prediction for low stress states). Nash and Ryde (2001) suggested to use $\log(\dot{\varepsilon})$ vs ε and Janbu (1969) suggested to use t vs $\dot{\varepsilon}^{-1}$ to get an objective interpretation of the creep parameter. As shown by Grimstad et al. (2015b) both these procedures give the same objective result.

As an example of the importance of proper selection of OCR and the creep ratio, the unified model for clay is presented and used in the following sections.

6.1 Example: the Unified Creep Model for Clay

For the clay model the OCR is for a general soil state calculated as a ratio between a state variable defining the size of a reference surface to an equivalent stress measure considering the stress state and other state variables like anisotropy and structure as given in equation (4).

$$OCR^{-\beta} = \left\langle \left(\frac{p' \cdot \left(1 + \frac{3}{2} \cdot \left\{ \frac{\boldsymbol{\sigma}_d}{p'} - \boldsymbol{\beta}_d \right\}^T \cdot \left\{ \frac{\boldsymbol{\sigma}_d}{p'} - \boldsymbol{\beta}_d \right\} \cdot g\left(\theta^\beta\right) \right)}{(1+\chi) \cdot p_{mi}'} \right)^\beta - OCR_{\max}{}^{-\beta} \right\rangle \tag{4}$$

Where p' is the mean effective stress $\boldsymbol{\sigma}_d$ is the deviatoric stress vector, $\boldsymbol{\beta}_d$ is the deviatoric anisotropy vector, χ is the unstable structure. $g(\theta^\beta)$ is a function defining the Lode angle dependency (i.e. the modified Lode angle), here a modified form of the Lade criterion (Lade & Duncan, 1975) is used. $OCR_{\max}$ is an optional parameter that gives a cut-off. The Macaulay brackets ensures a positive value when using the cut-off. p_{mi}' is a state variable defining the size of the intrinsic reference surface.

The volumetric creep strain rate converts into a general strain rate by equation (5), (Grimstad et al., 2008).

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\varepsilon}_v^{vp}\Big|_{oed} \cdot \frac{\partial Q}{\partial \boldsymbol{\sigma}'} \cdot \left\{ \frac{\partial Q}{\partial p'}\Big|_{oed} \right\}^{-1} \tag{5}$$

Where Q is the potential surface. In the unified creep model the potential surface is of similar shape as the reference surface (i.e. the surface of constant $OCR_{ref}^{-\beta}$ in equation (4)). However, a different deviatoric anisotropy vector ($\boldsymbol{\alpha}_d$) and a different Lode angle dependency for the critical state line $g_f(\theta^{\alpha})$ can be used, i.e. non-associated flow.

Some researchers like Yin and Graham (1999), Leoni et al. (2008) and Stolle et al. (1999) or Yin et al. (2002) assumed that there was no need for distinguishing between volumetric creep in a general stress state from the volumetric creep in e.g. the oedometer condition. This means that they assumed a constant size of the volumetric creep rate for a constant OCR regardless of state. Therefore, the critical state concept is lost and numerical issues close to the failure criterion appears. Figure 1 shows the consequence on the viscoplastic multiplier for different choices of formulations. As seen in the figure the formulation of e.g. Leoni et al. (2008) leads to a situation with no “dry” side and no “critical state”. The formulation of Yin et al. (2002) where the absolute value of the volumetric viscoplastic strain component is used, leads to a situation with two solutions (one going below and one going above the critical state line). It is clear that both these options lead to numerical instabilities close to the critical state line. On the other hand, eq. (5), used in the unified creep model, is a consistent formulation without any instability and has possibility for reaching “critical state”.

[Figure 1 near here]

6.2 *Demonstration of the clay creep model*

In this paper the Murro test embankment is revisited, this has previously been studied be e.g. Karstunen et al. (2015). Karstunen and Yin (2010) established visco-plastic parameters for the

Murro clay for the EVP-SCLAY1S model. Even though the mathematical form of the model used by Karstunen and Yin (2010) is different than the proposed unified model, their parameters for the layer with depth of 3.0 to 6.7 m corresponds to a value for β of about 25. When combining this number with the compressibility parameters, this leads to a value for μ^* of about 2.5e-3. Finally, using one day as reference time the corresponding *OCR* implicitly used by Karstunen and Yin (2010), for this layer, is approximately 1.2. Table 1 shows the β value, the *OCR*, the $OCR_{\max}$ and μ^* after converting the EVP-SCLAY1S parameters for all layers. Figure 2 shows how the two formulations compare for the layer between 3 and 6.7 m. An almost parallel shift of the curve indicates similar creep behavior of the two formulations within this range of strain rates. Note that the β values are varying between about 10 and 30 for the different layers. This is a large variation within a similar type of clay. At the same time, the *OCR* used is quite low. This is an indication for sample disturbance affecting the parameter selection e.g. $\beta = 25$ gives OCR = 1.52 after 100 years, assuming linear log(*OCR*) – log($\dot{\varepsilon}$) relationship. From the simulation results, the over-prediction of settlement in the bottom layers gives the same indication as the stress increase in this layer is moderate compared to the pre-consolidation stress. A reinterpretation with this in mind leads to parameters given by Table 2 and Table 3. Note that this study uses an average parameter set for layers 2 to 5. This will have some implications on giving a perfect match to the measurements. However, using average parameters is more relevant for engineering applications where normally only limited data is available. The remaining parameters are simply estimated based on experience from other sites and/or previous studies of the Murro clay. For more details on some of the index/state and hydraulic parameters, geometry or boundary conditions of the FE model see e.g. Karstunen and Yin (2010) or Sivasithamparam et al. (2015). In the analysis, large deformations are considered using updated mesh and pore water pressures. Figure 3 and Figure 4 give measured and calculated settlements for different locations versus time. The model and the simplified input captures the settlements reasonably well. Figure 5 shows the effect of ignoring creep on the calculated surface settlement.

[Table 1 to 3 near here]

[Figure 2 near here]

[Figure 3 to 5 near here]

7 Conclusion

In the CREEP project creep models for soft clay, peat and frozen soils were developed. The overstress method is in general appropriate to be applied for these materials. The paper demonstrates why a good settlement (creep) prediction depends on proper initialization of the model. This means that it is very important to select proper values for the parameters defining the initial strain rate. In general, a form of *OCR* is used to define strain rate. *OCR* should therefore not be mistaken for being an index property of the material or being related to preloading only (e.g. in the case for normally consolidated condition without considering the aging effect). Since it is often difficult to find a proper *OCR* from laboratory tests due to e.g. sample disturbance and test procedure, the recommendation is to check the initial strain rate for the selected *OCR*.

This paper also demonstrates the ability of the unified creep model for soft clay to simulate the behavior of the Murro test embankment. Normally only limited data is available in everyday engineering practice. Therefore, a simplified parameter set was selected in order to make the task more engineering like rather than a back-calculation. The results of the analysis show a good match between the measured and calculated values for settlements, when considering the simplified input. Since a perfect back-calculation was not the aim of this paper, further optimization of parameters will improve the results. This simple example demonstrates that the enhanced model can be a good engineering model for settlement analysis in geotechnical engineering.

The reader is also recommended to read the articles on frozen soil and peat that is given within this special issue of the Journal. The most important findings within the project for frozen soil is the introduction of the solid phase stress. For peat, including the effect of fibers in a peat model, though an overlay approach has shown to be very promising.

8 Notation

a_v parameter for bond degradation

C_c virgin compression index

C_α secondary compression index (void ratio based)

$C_{\alpha\varepsilon}$ secondary compression index (strain based)

c_k parameter for change in permeability with void ratio (slope of the line in the $e - \log k$)

e void ratio

e_0 initial void ratio

g^* flexibility parameter for shearing

k_h horizontal permeability

k_v vertical permeability

K_0 earth pressure coefficient at rest

K_0^{NC} earth pressure coefficient at rest in normally consolidated (NC) condition

l specific latent heat of fusion of ice

p' effective mean stress

p_{eq} equivalent stress measure

$p_{eq,c}$ equivalent pre-consolidation stress [$p_{eq,c} = p_{mi0} \cdot (1+\chi_0)$]

p_i ice pressure

p_w water pressure

p_{mi} size of intrinsic yield surface

p_{mi0} initial size of intrinsic yield surface

Q potential surface

q deviatoric stress

r_s time resistance number

S cryogenic suction

S_i ice saturation

S_w water saturation ($1 - S_i$)

T temperature on the thermodynamic scale

T_0 freezing/thawing temperature of water/ice at the given pressure

t time

$\boldsymbol{\alpha}_d$ deviatoric rotational vector for potential surface

β creep coefficient

β_{K0NC} scalar for rotation of reference surface under K_0^{NC} loading [$\beta_{K0NC} = 3/2 \cdot \boldsymbol{\beta}_{d0}^T \cdot \boldsymbol{\beta}_{d0}$]

$\boldsymbol{\beta}_d$ deviatoric anisotropy/fabric vector

$\boldsymbol{\beta}_{d0}$ initial deviatoric anisotropy/fabric vector

γ unit weight

$\boldsymbol{\varepsilon}$ total strain vector

$\boldsymbol{\varepsilon}^{vp}$ viscoplastic strain vector

ε_v volumetric strain

ε_v^{vp} viscoplastic volumetric strain

κ elastic compressibility parameter

λ_{i} intrinsic compressibility parameter

μ rotation parameter for reference surface and potential surface

μ^*, μ creep parameter

ρ_i density of ice

$\boldsymbol{\sigma}$ total stress vector

$\boldsymbol{\sigma}'$ effective stress vector

$\boldsymbol{\sigma}^*$ solid phase stress vector

$\boldsymbol{\sigma}_d$ deviatoric stress vector

φ friction angle for critical state

φ_{p} friction angle for peak of stress path in undrained shearing under NC state

χ_0 initial amount of structure

ω parameter for relative influence of shear on destructuration

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+ Ghoreishian Amiri et al. (2016)

+ Teunissen and Zwanenburg (2016)

Tables:

Table 1 Converted parameters from Karstunen and Yin (2010) to equivalent parameters for the unified model

Layer	Depth [m]	β	*OCR* (1 day)	OCR_{max}	μ^*
1	0 – 1.6	32.3	- (POP = 60 kPa)	1.415	2.05e-3
2	1.6 – 3.0	16.7	1.91	1.915	3.32e-3
3	3.0 – 6.7	24.4	1.18	1.180	2.48e-3
4	6.7 – 10.0	10.8	1.28	1.280	5.44e-3
5	10.0 – 15.0	29.0	1.17	1.170	2.32e-3
6	15.0 – 23.0	15.0	1.14	1.140	3.43e-3

Table 2 New interpreted unified model parameters for Murro clay

	Viscoplastic parameters			*Elastic parameters*		*Reference and potential surface parameters*					*Destructuration parameters*	
	OCR_{max}	μ_i^*	λ_i^*	κ^*	g^*	φ [°]	K_0^{NC}	β_{K0NC}	φ_p [°]	μ	a_v	ω
1	1.40	2.1E-3	0.067	0.004	0.004	39	0.40	0.60	30	45	3	0.3
2-5	1.50	2.9E-3	0.068	0.010	0.010	38	0.42	0.58	30	23	10	0.3
6	1.40	1.9E-3	0.060	0.004	0.004	35	0.50	0.45	30	30	7	0.3

Table 3 Parameters for/at initial state of Murro clay together with hydraulic parameters

			Earth pressure coefficient	*Structure*	*Void ratio*	*Permeability parameters*		
	OCR	γ [kN/m^3]	K_0	X_0	e_0	k_v [m/day]	k_h [m/day]	c_k
1	- (*)	15.8	1.10	2.0	1.6	1.6E−4	2.1E−4	0.40
2	1.80	15.5	0.50	4.0	1.8	1.6E−4	2.1E−4	0.44
3	1.25	14.9	0.42	9.0	2.5	1.8E−4	2.4E−4	0.55
4	1.35	15.1	0.42	8.0	2.2	9.0E−5	1.1E−4	0.50
5	1.40	15.5	0.42	5.5	1.8	5.5E−5	6.9E−5	0.44
6	1.40	15.9	0.50	6.5	1.5	8.3E−5	1.0E−4	0.34

*($\overline{p}_{eq,c} \approx 40$ kPa)

Figures:

Figure 1 Curves in normalized p′ - q space of constant dλ/dt for the alternative extensions using AMCCM as reference surface

Figure 2 Strain rate vs OCR in oedometer condition for EVP-SCLAY1S (Karstunen & Yin) and unified model (Grimstad et al.)

Figure 3 Measured and calculated vertical settlement versus time for different depths below the centerline of the embankment

Figure 4 Measured and calculated vertical surface settlement versus time for different distances from the centerline of the embankment

Figure 5 Comparison between analyses with and without creep

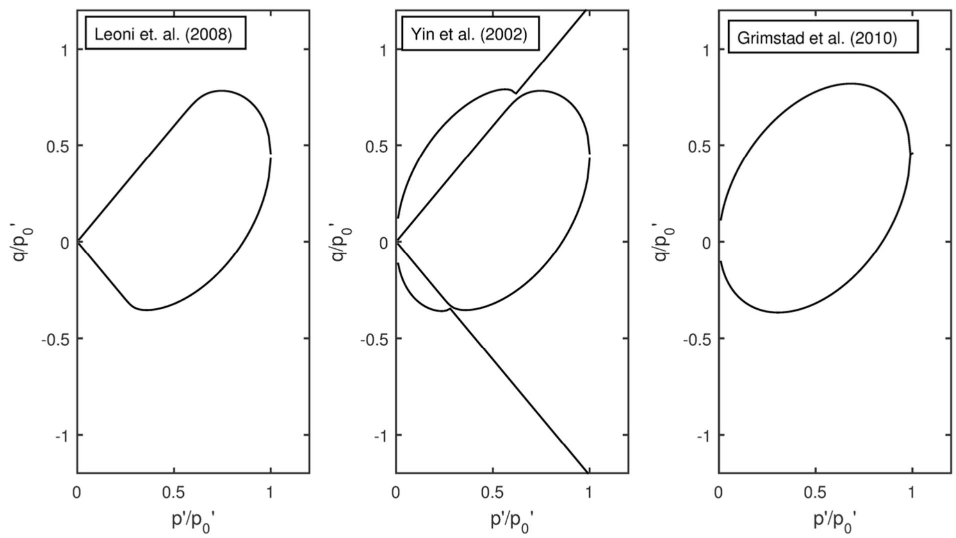

Figure 1 Curves in normalized p - q space of constant dλ/dt for the alternative extensions using AMCCM as reference surface

118x67mm (300 x 300 DPI)

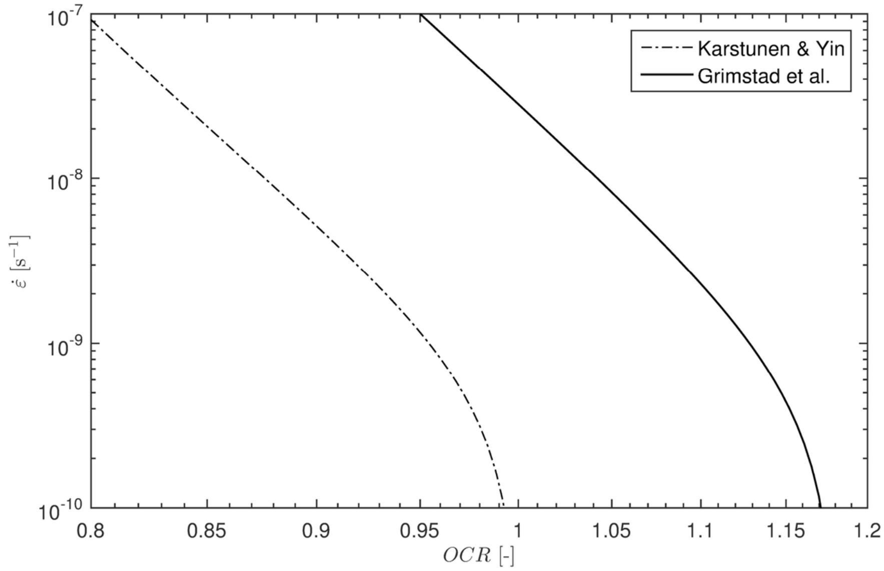

Figure 2 Strain rate vs OCR in oedometer condition for EVP-SCLAY1S (Karstunen & Yin) and unified model (Grimstad et al.)

125x76mm (300 x 300 DPI)

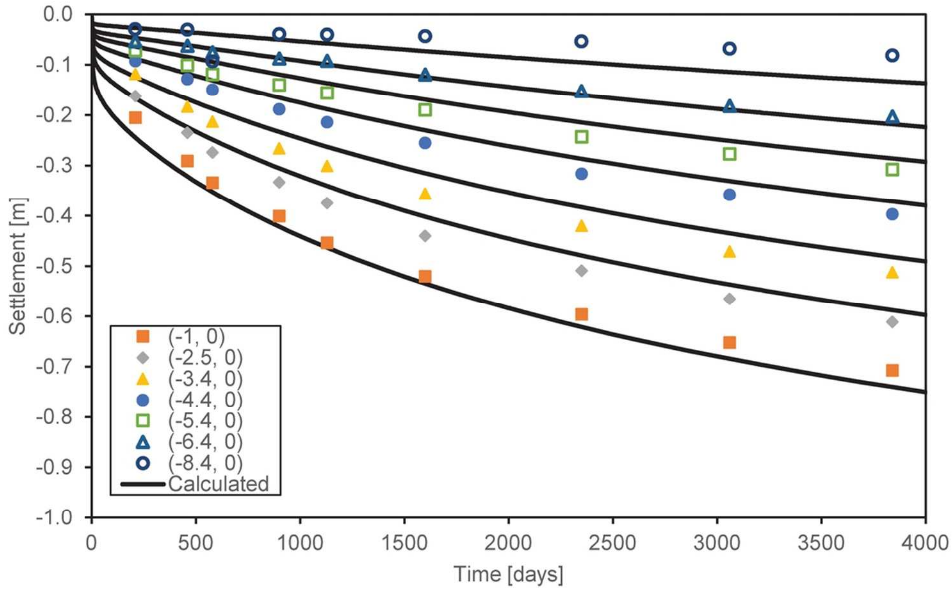

Figure 3 Measured and calculated vertical settlement versus time for different depths below the centerline of the embankment

101x63mm (300 x 300 DPI)

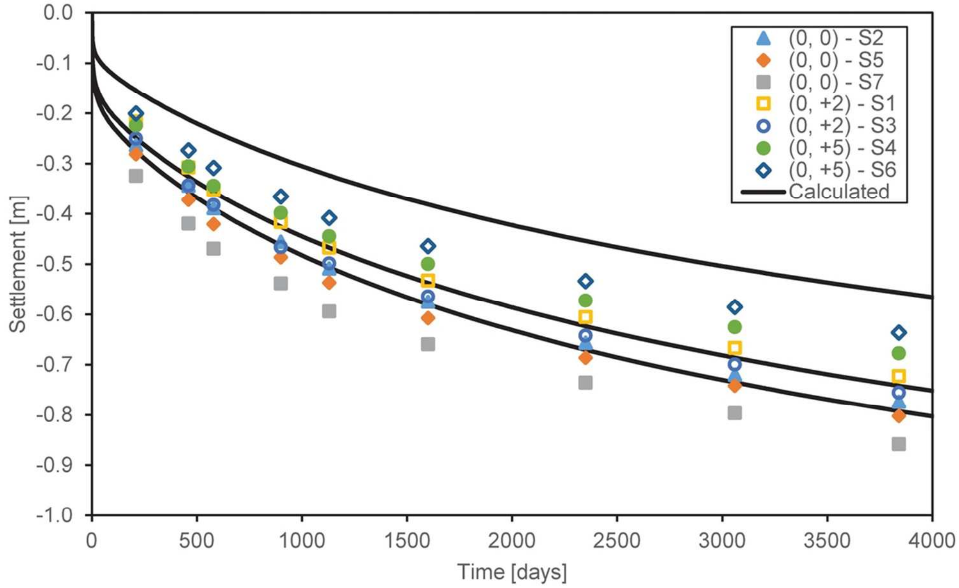

Figure 4 Measured and calculated vertical surface settlement versus time for different distances from the centerline of the embankment

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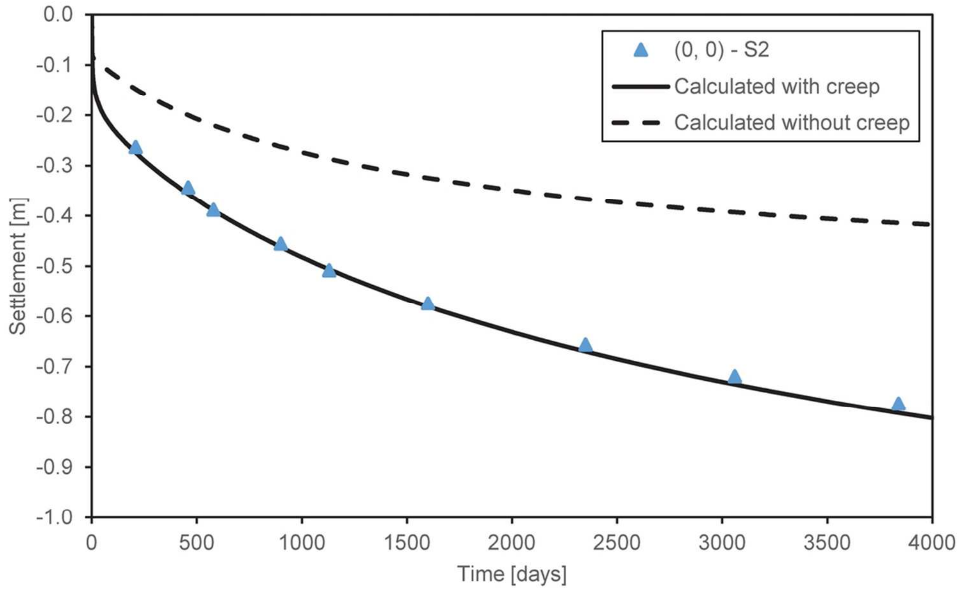

Figure 5 Comparison between analyses with and without creep

101x63mm (300 x 300 DPI)