IS THERE FUTURE FOR SOFT CLAY MODELLING?

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KEYWORDS

Constitutive modelling, Numerical modelling, Soft clay engineering

ABSTRACT

Constitutive models for natural sensitive clays have significantly evolved since the introduction of critical state models in 1950's. They can now be applied with high accuracy to geotechnical engineering problems as part of numerical analyses, thus assisting in geotechnical design. With the current rate-dependent models that combine initial anisotropy and its evolution, as well as the effects of bonding and destructuration, it is possible to capture the system-level response of a wide range of geotechnical problems in natural clays. Thus, a question arises if there is need for further developments in soft soil modelling. The paper will discuss the current state, followed by a discussion on future challenges that necessitate further developments. Despite the recent progress in model development, a major concern is that the gap between academia and practice is increasingly widening. Consequently, the geotechnical profession may not yet be able to fully exploit the latest modelling advances and the huge opportunities they offer for digitalisation and generation of training data for low probability events in geotechnics.

1. INTRODUCTION

The preference for the human population to live close to waterways, due to the good transport links and favourable conditions for farming, is the reason why mankind tends to live in areas underlain by soft soil deposits. In particular, the construction on soft sensitive clays in the Nordic countries comes with excessive costs and risks. Ideally, these risks are identified already in the planning stage, to avoid unnecessary delays, cost overruns and project cancellations. We may have been building on soft soils for thousands of years, but due to the unprecedented pressures from urbanisation and climate change, we are faced with additional challenges, and thus need new approaches.

Until now, the geotechnical design of road and railway embankments has relied on breaking up the problem into two separate analyses. We calculate

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the stability in undrained conditions of embankment slopes for the Ultimate Limit State (ULS) using Limit Equilibrium Method (LEM). That is followed by simple 1D consolidation analyses for settlements for the Serviceability Limit State (SLS), assuming groundwater levels and flow boundary conditions to be stationary. Similarly for natural slopes, LEM is the standard design method to assess stability, even though the accuracy of the analyses is unknown, as the design approach has no links with quantities we are able to monitor. The current methods of analyses are unlikely to remain adequate, as the future will entail more radical changes in pore pressures, temperature fluctuations and saturation levels. Furthermore, from stormwater drainage point of view, keeping the design alignment of embankments will become increasingly more important. Multi-dimensional displacement predictions under linear infrastructure, such as roads and railways, will become increasingly important.

In geotechnical engineering we cannot control the direction of loading. Yet, we need to design the foundation systems to be able to handle the external loads, as well as the body forces due to the self-weight of the soil and transfer them to layers with sufficient bearing capacity in the sub-soil. This needs to be done with a safety margin against failure that can be quantified. In parallel, we need to ensure the functionality of the geostructure during its design life. The loading directions in the soil in an urban setting are complex, as illustrated in Figure 1, where some typical total stress paths have been plotted in terms of mean stress (p) and deviatoric stress (q). Due to the low hydraulic conductivity and the viscous nature of natural soft clays, the emerging effective stress paths that control the stress-strain response, and the ultimate strength, are rate-dependent. The strain rates in laboratory tests differ from those in a geostructure in the field. The soil response for arbitrary loading paths thus needs to be generalised to map the rate- and time-dependent response from laboratory to the field.

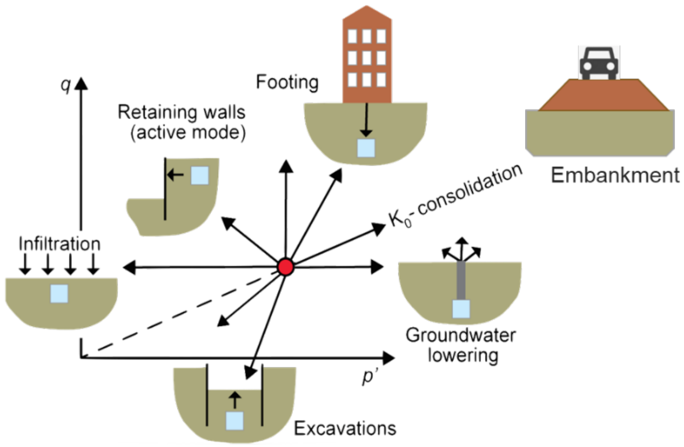

Figure 1 Examples of the complex total stress path associated with urban construction.

A logical method to accomplish the mapping across loading rates and length scales is to use a rate-dependent constitutive model, embedded into a coupled hydro-mechanical numerical framework.

The results of geotechnical numerical analyses largely depend on the constitutive model used to represent the soil response [36]. Furthermore, for accurately modelling natural soft clays, the accuracy of the model parameters relies strongly on the quality of soil sampling and testing [21]. Above all, the results rely on the ability of the geotechnical engineer in choosing a representative numerical model (that includes the selection of the constitutive model, numerical framework and boundary conditions) for the problem at hand, as well as deriving representative values for the model parameters and (initial) state variables.

The commercially available numerical codes utilise different numerical frameworks to solve the system of governing partial differential equations, considering equilibrium, strain compatibility, boundary conditions and stress-strain relationships. The numerical codes offer numerous, increasingly complex, constitutive models. Most of these constitutive models have been developed either via testing reconstituted soil samples, such as kaolin clay, or using generic data not designed to systematically test for the particular model features considered. Thus, element level comparisons between constitutive model simulations and experimental data found in geotechnical literature are often not a representative model validation for natural clays. Without access to raw data, it is also not possible to assess the quality of the data used for model validation. Consequently, only very few constitutive models have been validated against high-quality systematic data on intact samples of natural clays.

Finally, as important as the selection of the constitutive model is, the results of the numerical analyses are meaningless, unless the numerical framework adopted can ensure convergence within a well-defined tolerance. Fundamentally, all numerical models are approximations. The quality of results will thus depend on the general numerical framework utilised, which often includes assumptions that cannot controlled by the user. These include the solution methods for the non-linear equations and time integration methods, including the iterative procedures, sub-stepping schemes and converge checks adopted (at local and/or global level). Regardless, the user must be rather knowledgeable to properly discretise the problem, in selecting the correct model geometry, element types and boundary conditions, as well as the tolerances controlling the accuracy of the solution and the speed of the iterative processes.

Given the availability of user-friendly geotechnical numerical codes, people with limited background in numerical modelling per se are using these programs as black boxes for analysing complex problems, with constitutive models they do not truly master. So, no wonder many experienced geotechnical engineers are somewhat sceptical about what geotechnical numerical modelling can offer. The Ballina Embankment Prediction Symposium [42] highlighted how poor the predictions of the deformations of an embankment are, yet demonstrating significant progress from the settlement calculation competition on Haarajoki test embankment [48]. However, when geotechnical numerical analyses are done properly, they are powerful tools for understanding the complex time-dependent system response of geostructures and can assist the process of geotechnical design of both simple and complex cases.

The paper starts by discussing where we are now in terms of modelling sensitive clays. Following on, future challenges, opportunities and difficulties will be discussed.

2. WHERE ARE WE NOW IN SOFT SOIL MODELLING

The start of contemporary soft soil modelling can be attributed to the developments at the University of Cambridge in 1950s. Based on systematic testing of reconstituted kaolin clay, the unifying concepts of critical state soil mechanics were developed, ultimately resulting in the Modified Cam Clay (MCC) model [37]. With a single set of four model parameters and two state variables, i.e. specific volume (or void ratio) and preconsolidation pressure, it was possible to describe in a comprehensive manner the complex multi-dimensional stress-strain response of fine-grained soils, both in overconsolidated and normally consolidated state. In early 1990s, the MCC model and some of its derivatives were made available for practitioners via commercial finite element codes, such as SAGE Crisp, Z-Soil and Plaxis, making it possible to use the models in geotechnical boundary value problems. However, as the MCC model was developed for reconstituted clays, some of the key features of the response of natural clay were missing. Furthermore, the model significantly overpredicts the earth pressures in the normally consolidated state, resulting in poor predictions of horizontal displacements and earth pressures.

The pioneering research at Laval University in Canada, by Leroueil and his co-workers, highlighted some of the many complexities in the response of natural sensitive clays. Most importantly, the rate-dependency of the strength and stiffness was highlighted [29]. The anisotropy of yield, and the temperature effects on yielding, were also studied for example in Mexico, Canada, Finland and Sweden (e.g. [13], [26], [44]). Finally, the effects of bonding and degradation of the bonds, as typical for sensitive clays, see e.g. [9] and [30], became better understood.

Observing experimentally the soil response, however, is not sufficient. Even though e.g. [12] and [34] proposed elasto-plastic model frameworks that account for initial anisotropy and its evolution with irrecoverable strains, there was no systematic data for formulating the kinematic hardening laws. Many of the experimental researchers above only studied the shape of the initial yield envelope. This major gap was tackled by the author and her co-workers by systematically testing four very different Finnish clays, both in their natural and reconstituted state (see e.g. [49], [24], summarised in Koskinen [27]. Using the ideas by Gens & Nova [15], the S-CLAY1 model [49] was extended to account for the bonding and degradation of bonds in sensitive clays [25]. The resulting S-CLAY1S model [25], however did not include the essential rate-effects and creep. Thus, by utilising the ideas of Leoni et al. [28] & Grimstad et al. [18], Creep-SCLAY1S model was developed [40], [17]. With the current version of Creep-SCLAY1S, a rate-dependent model that combines initial anisotropy and its evolution, as well as the effects of bonding and destructuration, it is possible to capture the system-level response for many geotechnical problems, such as embankments and excavations, as discussed in the following.

3. MODELLING GEOSTRUCTURES ON NATURAL CLAYS

For accurate predictions using a numerical model, the laboratory testing programme needs to be planned to suit for the constitutive models to be selected. For Creep-SCLAY1S, a systematic test series needs to be performed for each representative soil layer. The test series should consist of CRS (constant rate of strain) & IL (incrementally loaded) oedometer tests to assess the preconsolidation pressure, compressibility and hydraulic conductivity. For strength estimation, CAUC triaxial tests (anisotropically consolidated undrained shearing in compression) are needed. Additionally, for problems where both SLS and ULS are important, or significant rotations of principal stresses are expected, an undrained triaxial test sheared in extension (CAUE) is recommended. For problems where large amplitude loading/unloading loops are encountered, it is also important to plan tests with appropriate loading-unloading loops. The effect of sample disturbance can be quantified by using the sample quality metrics, e.g. by Lunne et al. [32], considering the sample quality relative to the initial state ($\Delta e/e_0$, with Δe being the change in void ratio when consolidating to the in situ effective stress state at a corresponding void ratio of e_0).

The next step is to derive the values for the model and state parameters. For those parameters that cannot be directly derived, recommendations in [16] can be used, followed by calibration of the parameter set via element level simulations (see https://soilmodels.com/calibsoftware/ for examples of single element drivers). Once the calibration is completed, i.e. that the test response along different loading paths can be simulated with a single set of parameters, we are ready for numerical analyses. Calibrating parameters for a relatively simple model, such as MCC, is more difficult than for Creep-SCLAY1S that captures the overall response of natural clays more accurately than MCC.

As summarised in [22] [23], Creep-SCLAY1S has been used successfully to simulate test embankments, such as Haarajoki [3] and Ballina tests embankments [4]. More recently, the Onsøy test embankment [6] [7] was simulated considering both SLS and ULS, including the time for failure (preliminary results by Hernvall shown in [22]. The simulations of the Göta tunnel excavation [46], a permanent sheet pile wall in Uppsala [45], the Marieholm tunnel (yet unpublished) and the lime-cement-column -supported excavation in Gothenburg central station [8] demonstrate the ability of the Creep-SCLAY1S model to capture the time-dependent system response of embedded retaining structures. The latter include the wall movements, the generation and dissipation of pore pressures, strut forces and induced ground movements. However, the larger the distance from the excavation, the poorer is the match between the simulations and measurements. The likely reason for that is the poor performance at small strain magnitudes. A small-strain feature was recently added to the model formulation, to overcome this limitation, following the ideas by Sivasithamparam et al. [41]. Furthermore, the visco-plastic model formulation of Creep-SCLAY1S enables extension of the model for other long-term predictions, such as cyclic degradation [51] in soft natural clays due to railway traffic.

While Creep-SCLAY1S can be used for individual case studies and forecasting, the true power comes from understanding the system performance and thus model simulations can be used for generalisation of the system performance. As an example of the former, Hernvall et al., [19], used the model for studying the increase of the stability of an embankment as a function of time. In the FE analyses of [19] the mobilised strength along the failure plane is automatically predicted by the constitutive model, even accounting for strain softening. This overcomes difficulties in evaluating the evolution and mobilisation of the undrained shear strength along the failure surface. Tornborg et al. [47] in turn used numerical analyses in combination with non-dimensional groups to create design charts for the effective heave pressure that develops over time under the slab at the bottom of a deep excavation.

As shown by Sellin [38], the rate of loading to failure affects both the time of failure of natural slopes, as well as the mode of failure (i.e. the depth and extent of the failure surface). Furthermore, using a simpler model, such as an isotropic model or a model with fixed anisotropy is not conservative [39]. Moreover, in natural slopes and in sloping ground, the initialisation (of the initial state variables) is a challenge that requires careful consideration [38] [46]. This definitely needs further investigation, as the initialisation affects the mobilised undrained shear strength in natural slopes.

In the West Coast of Sweden the natural slopes have been formed by erosion processes. Sellin [38] simulated the formation of a typical slope by numerically modelling the erosion process. The in Figure 2d, suggest that due to these processes, the slope has become overconsolidated.

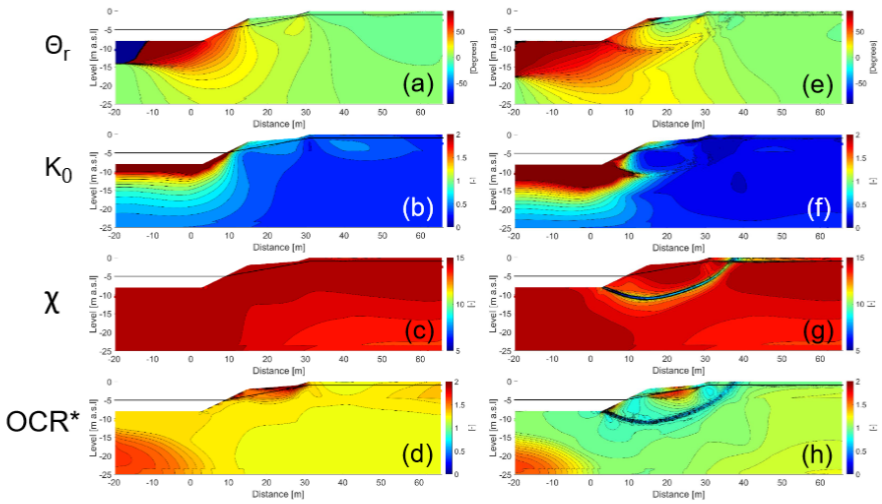

*Figure 2 Contour plots of principal stress direction Θ_r (upper row), K_0 (second row), χ (third row) and modified over consolidation ratio OCR * (lower row) after unloading (left) and after additional gravity is applied to drive the slope to failure (right) [38].*

The erosion process was found to cause significant rotation of principal stress axes, changes in K_0 (coefficient of earth pressure at rest) and the amount of bonding χ . These changes in the state of the soil will affect the stability and mode of failure, when the slope is subsequently driven to failure by increasing the gravity (see Figure 2 on right). Our knowledge of the rate-dependent response of natural clays in the overconsolidated region is very limited, and systematic experimental investigation and combined with model development is required. For understanding the movements and vulnerability of existing slopes in sensitive clays, it instrumental to study the strength upon unloading and rotation of principal stress axes, which is far from trivial.

4. CHALLENGES IN NEAR FUTURE

In the Nordic countries, like in most of the developed world, most of our transport infrastructure is ageing. Thus, characterisation of the state of existing transport infrastructure is of utmost importance, to enable predictive maintenance and smartly designed timely upgrades. The latter include e.g. increasing embankment heights in preparedness for new flood levels, replacing culverts in the view of extreme rainfall incidents, as well as widening of existing embankments to increase the capacity. Increasing traffic and axle loads also imply that our roads and railways are facing increased static, cyclic and dynamic loading. This paired with increasing number of environmental loading cycles due to climate change (droughts vs. downpours, number of freeze-thaw cycles), creates additional challenges and demands for our ageing infrastructure. Thus, we need model developments that enable us to predict future extreme events (with low probability) starting from the current state that often is unknown.

Due to climate change, we will experience more extreme drying-wetting cycles, and there will be a notable increase in the periods of intense precipitation and drought. The more extreme temperature fluctuations will affect in particular the surface layers in the ground, such as the pavement structures and the dry crust, potentially accelerating deterioration and cracking. In the Nordic countries, the increases in the annual number of freezing-thawing cycles [43] and fluctuations of pore pressures, have already increased the demand for maintenance, as well as caused embankment and slope failures in unexpected locations [33].

Both the mobilised shear strength and the stiffness are functions of effective stress, which is controlled by suction (the negative pore pressures), affecting the most critical shallow modes of failure in natural and man-made slopes. As demonstrated in [31], even small increases in temperature will accelerate creep in sensitive clays, resulting in increases in the rate of ground movements when the effective state is close to the preconsolidation pressure. The effects of these climate-change driven changes need to be quantified, to understand which issues are most important in a given environmental setting and geotechnical engineering problem. This requires multi-physics models, currently being developed at Chalmers [1]. Understanding the role of vegetation in the current safety levels is also a multi-physics problem [43]. Consequently, development of advanced physics-based numerical models for natural clays should be a high priority.

Historically, geotechnical design of underground construction and the potential impacts on the surroundings, both in the short and long term has been made with 2D simulations. In Geotechnical Engineering context the simulations are fully coupled transient analyses in either axisymmetric or plane strain conditions. Hydrogeologists may also consider 3D groundwater flow simulations that are weakly coupled with 1D settlement simulations. Most simulations consider so-called green-field conditions when estimating possible building damage from underground construction, thus largely ignoring the effect of foundations. New constructions inevitably affect the existing structures and buildings, some with high cultural and/or historic value. Thus, there are more demands on combining predictions and monitoring. Monitoring alone is insufficient, as the rigorous use of Observational Method [35], relies on predictions of the quantities that are being monitored, to set up the trigger levels. In case of tunnels and deep excavations, this means (vertical and horizontal) displacements, stresses and pore pressure changes, the latter often affecting large areas. The problems we need to analyse are 4D, with time as the 4th dimension. Thus, from a project-scale we need increasingly to move to regional scale, as demonstrated in [50].

In an urban environment, the site characterisation needs to consider, in addition to the geological history, the effects of anthropological loading history. The installation effects of retaining structures, piles and ground improvement in soft soils often result in ground movements that are of the same order of magnitude as the effects of the excavation and tunnelling themselves. Numerical modelling can be used to simulate these processes (see e.g. [10] [14] [20]. The deepening of waterways and canals and the deposition of fills in and next to the waterways for new developments, as well as historic land and water use may cause significant background subsidence. An example is Gothenburg, with background creep settlements varying between 3 mm/year to over 30 mm/year. The cumulative effects of these in tens of years (the planned lifetime of building and infrastructure) and hundreds of years (flood protection), means that the background creep settlement cannot be ignored. They need to be considered in all planning and design of new developments, as they affect the connections of infrastructure to buildings and most importantly, future flooding scenarios. Namely, the background creep settlements are rarely uniform, and thus areas that were not deemed flood-prone based on their current elevation may in the long-term perspective become vulnerable for floods (due to the settlements from fills). Fortunately, new sources of monitoring data that cover large areas, e.g. InSAR data from the European Ground Motion Service [11], can assist in identifying areas with elevated long-term risks. The measurements on the surface will of course not suffice, and need to be complemented with depth-integrated measurements of pore pressures and displacements to understand the source and nature of the time-dependent deformations at the surface.

All in all, as discussed above, future geotechnical design cannot be based on simplified semi-empirical methods, as we no longer have the conditions for which those methods have been calibrated for, and most importantly we do not have experience on those conditions. As a result of urbanisation and climate change, we have to be able to understand ever more complex systems of systems, and thus, we will increasingly need to rely on physics based numerical modelling to understand, and predict, the performance of these complex systems in a changing environment.

5. OPPORTUNITIES & DIFFICULTIES

In society at large, as well as in the construction industry, there are huge expectations on using artificial intelligence (AI) and big data to make processes more efficient and predictions more reliable. Furthermore, there is the impression that the conservatism (as expressed in safety factors) can be reduced. Yet, there are several obstacles that preclude the use of AI and big data in geotechnical engineering:

1) The low probability of most extreme events (storms, floods, slope failures, bearing capacity problems) implies that, even in case we can monitor all these events, there is an insufficient amount of data for developing AI-based techniques. There is a significant opportunity to use the physics-based numerical models discussed herein to for example train meta-models (a simplified surrogate model) that are computationally more efficient for analysing large scale problems [50].
2) For serviceability limit state, there is opportunity to use data driven approaches. Yet, the often-poor reliability of the data and the incompleteness of the datasets prevents the widespread use of purely data-driven approaches. A method to overcome some of the limitations of the data reliability and sparsity is to combine site investigation and monitoring data with numerical forecasting (prediction) models using Data Assimilation [2], as demonstrated in Figure 3.
3) There is a general lack of access to high quality public data that is in digital format and properly annotated. Furthermore, the geotechnical quality and reliability (quality of the soil samples tested in the laboratory, reliability of the porewater transducers in the ground after some time, control of temperature) is not always sufficient. Major players in Swedish geotechnical engineering, such as Swedish Geotechnical Institute, Swedish Geological Union, Trafikverket and municipalities have already been developing great tools. What is needed is to integrate those resources in a fully open database linked to other resources such as Land Survey (Landmäteriet) and Swedish Meteorological and Hydrological Institute (SHMI).

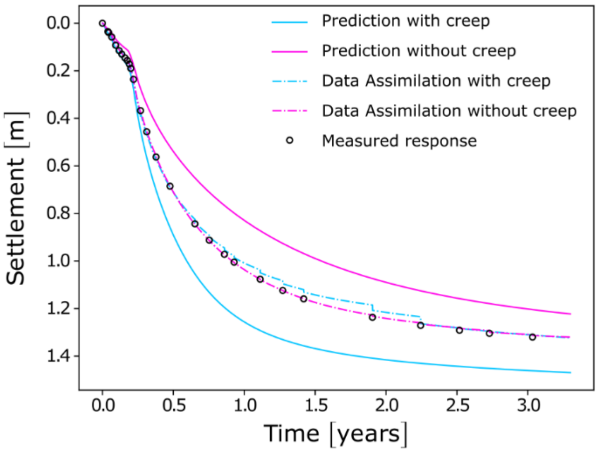

Figure 3 Prediction of settlement of Ballina test embankment with and without creep, combined with data assimilation (modified from [2]).

Finally, the developments discussed above require a strong commitment to further develop physics-based models that are tailored to the Nordic conditions. In addition, we need to reinforce our efforts to not only teach geotechnics, but also the opportunities and limitation of numerical modelling and computational methods associated to AI and big data. The education does not stop at university, there is an imminent need for the discipline to develop a framework for life-long learning in geotechnical engineering.

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