# Evaluation of Anisotropic Creep Model at Embankment Level

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ABSTRACT: A new constitutive model (Creep-SCLAY1) for rate-dependent behaviour of anisotropic clays has been recently proposed. Stemming from previously developed anisotropic creep model (ACM), creep is formulated using the concept of a constant rate of visco-plastic multiplier. Anisotropy is taken to account by introducing a fabric tensor to represent the rotation of the constitutive surfaces. Moreover, a rotational hardening law describes the evolution of anisotropy due to volumetric and deviatoric creep strain rates. A key assumption in the model formulation is that there is no purely elastic domain. In this paper, numerical simulations of the Murro test embankment on soft soils have been carried out, in order to investigate performance of the proposed model compared to previously developed ACM model. The numerical simulations show that the Creep-SCLAY1 model is able give a better representation of natural clay behaviour at a trial embankment level.

## 1 INTRODUCTION

In recent years more and more construction like embankments and buildings have been built on soft soils. Natural soft soils behave in a highly anisotropic manner due to the deposition process and subsequent loading history, and show rate-dependent (e.g. strain-rate effects, creep, relaxation and accumulated effects) behaviour. An accurate description of anisotropy and rate-dependent behaviour of soft soils is necessary for safe and economic design of structures on soft soils deposits. Researchers started to address the study of soft soil since the beginning of last century.

To obtain realistic solutions for geostructures on natural clays, it is essential to use a constitutive model that accounts for anisotropy and rate-dependency. Many constitutive models for rate-dependency and anisotropy have been proposed in the literature. Major step forward was the introduction of the overstress theory (Perzyna, 1963) which led to a development of several three dimensional creep models. Firstly, isotropic models were proposed using modified Cam-clay ellipses as boundary between purely elastic and elasto-viscous region as postulated in Perzyna's overstress theory. As isotropic ellipses are inadequate to capturing the natural soft soil behaviour, new generation of anisotropic rate-dependent models were proposed. Sekiguchi-Ohta (1977) proposed an anisotropic rate-dependent model using non-stationary flow surface theory to capture rate-dependent behaviour, but anisotropy was formulated as an initial rotation of constitutive ellipses which stay fixed.

Recent studies on reconstituted samples (e.g. Hicher et al. 2000) show that particles orientation and contacts changes during irrecoverable straining at microstructural level. This can be postulated in macro-level that anisotropy can evolve when undergoing large strains. Based on experimental studies on natural Otaniemi clay, Wheeler et al. (2003) proposed an elasto-plastic model, called S-CLAY1, with a rotational hardening law describing the changes in the inclination of the yield surface due to irrecoverable straining. The calibration of the parameters for the S-CLAY1 model is rather straightforward and the model has been thoroughly validated experimentally by Karstunen and her coworkers (Karstunen & Koskinen, 2004 and 2008).

Recently, as in its elasto-plastic (S-CLAY1) counterpart, rate-dependent behaviour models that account for initial (inherent) and evolution (creep strain induced) of anisotropy have been proposed (e.g. Leoni et al., 2008: Karstunen and Yin 2010: Grimstad et al., 2010: Yin et al., 2011: Sivasithamparam et al., 2015).

The Creep-SCLAY1 (Sivasithamparam et al., 2015) is an extension of the anisotropic creep model (ACM) proposed by Leoni et al. (2008). The ACM incorporates rotated ellipses (similar to the S-CLA Y1 model) used as contours of volumetric creep strain rates. However, the Creep-SCLAY1 model differs considerably from the ACM in the formulation of creep strain rates. Creep is formulated in Creep-SCLAY1 using the concept of rate of the viscoplastic multiplier (Grimstad et al. 2010). Unlike Grimstad et al. (2010) model that used Janbu's time resistance concept, the present model uses the more familiar creep coefficient, modified creep index $\mu^*$ which can be easily derived from standard laboratory tests.

## 2 CONSTITUTIVE MODEL - CREEP-SCLAY1

For the sake of simplicity, the mathematical formulation of the model is presented in triaxial stress space. The extension to more general stress space can be found in Sivasithamparam et al. (2015).

The outer rotated ellipse (see Fig. 1) defines the Normal Consolidation Surface (NCS), i.e. the boundary between small and large creep strains, and the size of this ellipse evolves with volumetric creep strains according to the hardening law

$$p_p' = p_{p0}' exp\left(\frac{\varepsilon_v^c}{\lambda^* - \kappa^*}\right) \tag{1}$$

where $\lambda^*$ and $\kappa^*$ are the modified compression index and modified swelling index, respectively. The intersection of the vertical tangent to the ellipse with the $p'$ axis is the isotropic preconsolidation pressure $p_{p0}'$. The inner ellipse passes through the current state of effective stress called the Current Stress Surface (CSS). The intersection of the CSS with the horizontal axis is called the equivalent mean stress $p'_{eq}$, and it is defined as

$$p_{eq}' = p' + \frac{(q - \alpha p')^2}{(M^2(\theta) - \alpha^2)p'} \tag{2}$$

where M(θ) is the stress ratio at critical state (dependant on Lode angle θ) and α is a scalar quantity used to describe the orientation of the normal consolidation surface and current stress surface.

Creep is formulated using the concept of a constant rate of visco-plastic multiplier, following the idea of Grimstad et al. (2010) as follows

$$\dot{\Lambda} = \frac{\mu^*}{\tau}\left(\frac{p_{eq}'}{p_p'}\right)^{\beta}\left(\frac{M^2(\theta) - \alpha_{K_0^{nc}}^2}{M^2(\theta) - \eta_{K_0^{nc}}^2}\right) \tag{3}$$

where the additional term $(M^2(\theta) - \alpha_{K^{nc}}^2)/(M^2(\theta) - \eta_{K^{nc}}^2)$ is added to ensure that under oedometer conditions, the resulting creep strain corresponds to the measured volumetric creep strain rate. $\alpha_{K_0^{nc}}$ defines the inclinations of the ellipses in normally consolidated state and $\mu^*$ is the modified creep index. $\mu^*$ and β are defined as

$$\beta = \frac{\lambda^* - \kappa^*}{\mu^*} \qquad \mu^* = \frac{C_\alpha}{\ln 10\,(1 + e_0)} \tag{4}$$

where $c_\alpha$ is the one-dimensional secondary compression index and $e_0$ is initial void ratio.

In addition to the volumetric hardening law, the Creep-SCLAY1 model incorporates a rotational hardening law that describes the changes in the orientation of the normal consolidation surface with creep straining.

$$d\alpha = \omega\left(\left[\frac{3\eta}{4} - \alpha\right]\langle d\varepsilon_v^c\rangle + \omega_d\left[\frac{\eta}{3} - \alpha\right]|d\varepsilon_d^c|\right) \tag{5}$$

where $d\varepsilon_d^c$ is the increment of creep deviatoric strain, and ω and $\omega_d$ are two additional soil constants.

For further details of the model formulation, implementation and validation, the reader is referred to Sivasithamparam et al. (2015).

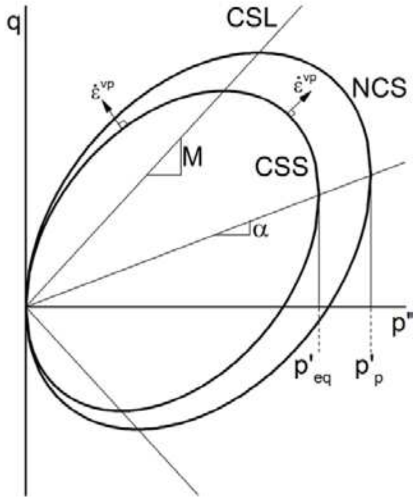

Fig. 1 Current State Surface (CSS) and Normal Consolidation Surface (NCS) of the Creep-SCLAY1 model and the direction of viscoplastic strains (triaxial stress space).

## 3 MURRO TEST EMBANKMENT

The Murro test embankment was constructed on a 23 m deep deposit of medium sensitive clay near the town of Seinäjoki in Western Finland. The embankment has been monitored for a long time, since it was built in 1993, and it has been subjected to several studies (see e.g. Karstunen et al., 2005) due to decent instrumentation and extensive non-standard laboratory testing (for details see Karstunen and Yin, 2010). The almost normally consolidated clay is overlain by a 1.6 m thick overconsolidated dry crust and the underlying thick clay layer is almost normally consolidated and relatively homogeneous. The groundwater table is estimated to be at 0.8 m below ground level. Murro clay is highly strain anisotropic and time-dependent (Karstunen and Yin 2010 and Karstunen et al., 2012). The Murro test embankment is 2 m high and 30 m long with a gradient of slope of 1:2.

The width of the top of the embankment is 10 m. Construction of the embankment was completed in two days.

The construction and consolidation of Murro test embankment has been modelled with a plane strain finite element analysis using PLAXIS 2D Version 2012. Due to the symmetry of the problem, only half of the embankment was considered in the analyses. Fig. 2 shows the geometry and soil layers of Murro test embankment. The problem was simulated as large strain analysis using updated mesh and pore water option in PLAXIS. The finite element model was discretized by using mesh consisting of 1416 15-noded triangular elements following mesh sensitivity studies. The construction of the embankment was simulated as an undrained calculation phase followed by a fully coupled consolidation analysis. The granular embankment fill was modelled with the simple linear elastic perfectly plastic Mohr Coulomb model using the following values E=40000 kN/m$^2$, $\nu'$=0.35, $\varphi'$=40°, $\psi'$=0°, c'=2 kN/m$^2$, and $\gamma$=21 kN/m$^3$. Karstunen et al. [38] divided the clay deposit into 7 layers based on available test data. Required parameters for Creep-SCLAY1 model were obtained from Karstunen et al. [39] and are summarized in Tables 1-2.

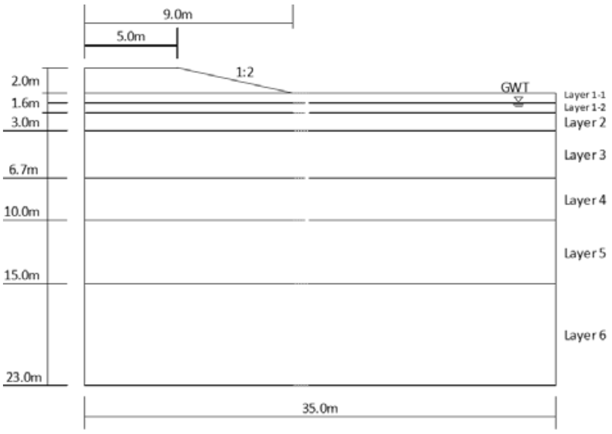

Fig. 2. Geometry of Murro test embankment

Fig. 3(a) shows the measured vertical settlements at centre-line and 2 m off the centre-line, underneath the embankment, together with the Creep-SCLAY1 and ACM model predictions. Very good agreement is achieved between the measured and predicted settlements with Creep-SCLAY1. In contrast, the ACM model overpredicts the vertical settlement versus time compared to Creep-SCLAY1.

Fig. 3(b) presents the comparison between the predicted and measured horizontal displacements, underneath the toe of the embankment, by the Creep-SCLAY1 and ACM model. Very good agreement is achieved between the measured and predicted results with Creep-SCLAY1, although for the early stage of consolidation the horizontal displacements were overestimated. However, ACM significantly overpredicts the horizontal displacement, and even the predicted trend under the toe is not correct. This is due to the assumption of constant volumetric creep strain rates which results in shear strains being overestimated.

## 4 CONCLUSIONS

In this paper a recently developed anisotropic model accounts for creep behaviour is used in a numerical simulation of Murro test embankment. The results demonstrate that the Creep-SCLAY1 model gives realistic predictions. When compared with field deformations, in contrast to the predictions by ACM the proposed model has a very good match with the measured data, both qualitatively and quantitatively.

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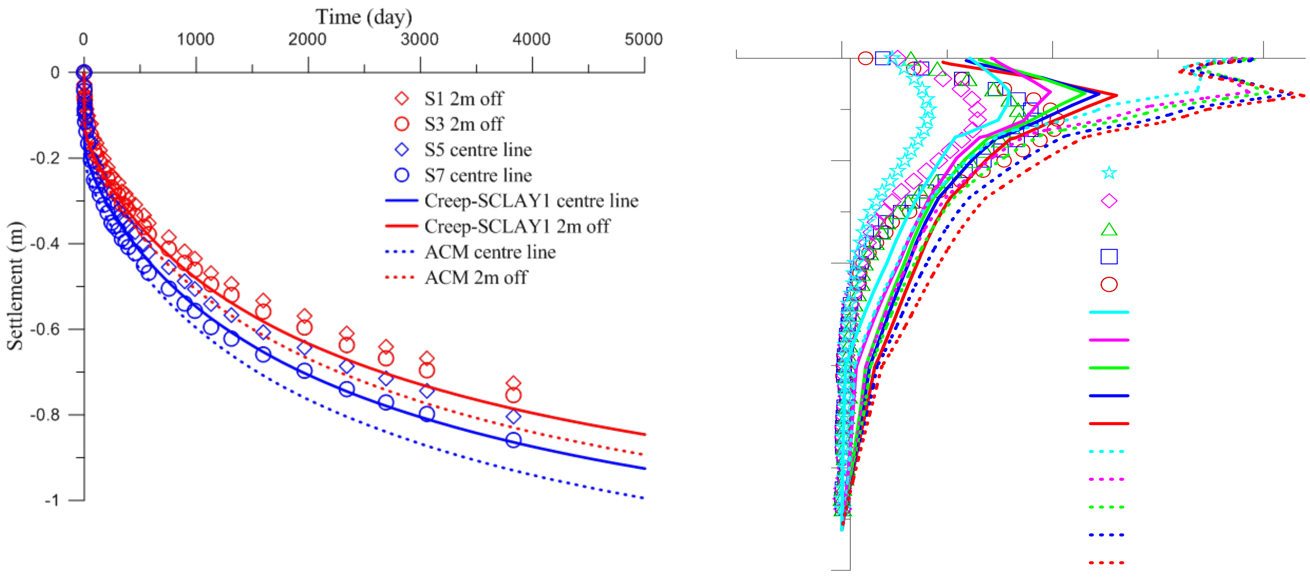
Table 1: Murro embankment parameters

| Layer | Depth<br>m | POP<br>kPa | $e_0$ | $\alpha_0$ | In-situ $K_0$ | μ* | τ<br>day | γ<br>kN/m3 |
|---|---|---|---|---|---|---|---|---|
| 1-1 | 0.0-0.8 | 20 | 1.4 | 0.63 | 1.25 | 8.69E-04 | 1 | 15.8 |
| 1-2 | 0.8-1.6 | 10 | 1.4 | 0.63 | 1.25 | 8.69E-04 | 1 | 15.8 |
| 2 | 1.6-3.0 | 2 | 1.8 | 0.63 | 0.34 | 2.33E-03 | 1 | 15.5 |
| 3 | 3.0-6.7 | 2 | 2.4 | 0.63 | 0.35 | 1.92E-03 | 1 | 14.9 |
| 4 | 6.7-10.0 | 2 | 2.1 | 0.63 | 0.40 | 1.52E-03 | 1 | 15.1 |
| 5 | 10.0-15.0 | 2 | 1.8 | 0.63 | 0.42 | 1.49E-03 | 1 | 15.5 |
| 6 | 15.0-23.0 | 2 | 1.5 | 0.63 | 0.43 | 7.30E-04 | 1 | 15.9 |

Table 2: Murro embankment parameters

| Layer | $\nu'$ | $M_c$ | $M_e$ | $k_x$<br>m/day | $k_y$<br>m/day | ω | $\omega_d$ | λ* | κ* |
|---|---|---|---|---|---|---|---|---|---|
| 1-1 | 0.35 | 1.6 | 1.04 | 2.13E-04 | 1.64E-04 | 45 | 1.02 | 0.0667 | 4.20E-03 |
| 1-2 | 0.35 | 1.6 | 1.04 | 2.13E-04 | 1.64E-04 | 45 | 1.02 | 0.0667 | 4.20E-03 |
| 2 | 0.35 | 1.6 | 1.04 | 2.13E-04 | 1.64E-04 | 25 | 1.02 | 0.1786 | 1.07E-02 |
| 3 | 0.10 | 1.6 | 1.04 | 1.78E-04 | 1.34E-04 | 20 | 1.02 | 0.1471 | 1.06E-02 |
| 4 | 0.15 | 1.6 | 1.04 | 1.10E-04 | 9.07E-05 | 25 | 1.02 | 0.1161 | 9.07E-03 |
| 5 | 0.15 | 1.6 | 1.04 | 6.85E-05 | 5.48E-05 | 25 | 1.02 | 0.1143 | 1.21E-02 |
| 6 | 0.15 | 1.6 | 1.04 | 1.04E-04 | 8.22E-05 | 30 | 1.02 | 0.0560 | 1.60E-03 |



(a) time-settlement

(b) horizontal displacement under toe

Fig.3. Comparison between measured and predicted results – Creep-SCLAY1 versus ACM