DISCUSSION

Anisotropic creep model for soft soils

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The anisotropic creep model (ACM) is described as an advance on earlier isotropic creep models (ICM). The relative merit of both models has been studied for Dutch peat and organic clay, and it appears that the isotropic version is to be preferred. Further, the equations governing one-dimensional creep are investigated.

Two cases of embankments on peat and organic clay have been recently postdicted with the finite-element method, applying the ICM model to the soft soils, and obtaining the necessary parameters using a constant rate of strain (CRS) K_0 oedometer (Den Haan & Feddema, 2009). The volumetric compressibility parameters are high as expected, but so is the critical state parameter M , with no cohesion being assumed. One case concerns the Betuwe railway embankment near Sliedrecht, built on 7.5 m of soft organic clays and peat. Fig. 17 shows that M values are high and correlate negatively with bulk density and positively with organic content. These are notable characteristics of organic soils, confirming results by Coutinho & Lacerda (1989), Den Haan (1995) and Den Haan & Kruse (2007). The other case is the IJkdijk trial embankment at Booneschans where a peat layer of 2 m thick dominated deformations, and was modelled with $M=2.6$, which again is very high. Satisfactory fits were obtained, both for settlements and for horizontal deformations, in both cases.

Den Haan & Kamao (2003) were able to fit an ICM model to the results of triaxial compression and K_0 oedometer tests on organic Oostvaardersplassen clay, again using high M values. From equation (26) it follows that M_I in the ICM and M_A in the ACM are related by

$$M_I^2 \approx M_A^2 + 3\alpha_0 \quad (44)$$

and the ACM therefore has substantially lower values of M than the ICM. It therefore appears that the refinement of the ACM model is both unjustified and unnecessary in organic soils with high M .

The validity of equation (26) is now investigated. When

Fig. 17. Cam-clay M parameter of soft Sliedrecht soils obtained from CRS K_0 oedometer tests, and applied in finite-element postdiction of embankment deformations

applying the ACM to the results of the CRS K_0 oedometer, the angle of anisotropy α and M interact in the equation

$$\frac{\dot{\gamma}^c}{\dot{\epsilon}_{vol}^c} = \frac{2(\eta_{0,crs} - \alpha_0)}{M^2 - (\eta_{0,crs})^2} = \frac{2(\lambda/\kappa) - (\eta_{0,crs}/\eta_{0,el})}{3(\lambda/\kappa) - 1} \quad (45)$$

where, with the subscript 0 denoting the normally consolidated one-dimensional condition, $\eta_{0,crs}$ is measured at constant rate of strain, λ/κ is the ratio of the compression and swelling indices and $\eta_{0,el}$ is the elastic one-dimensional condition determined by Poisson ratio ν . This equation also applies in the inviscid case. It applies to the viscid models when constant rate of strain is applied and the soil has reached the normally consolidated state. When one-dimensional creep is applied with constant σ'_v , the stress ratio migrates gradually to the state where elastic strain rates vanish (Den Haan, 2002)

$$\frac{\dot{\gamma}^c}{\dot{\epsilon}_{vol}^c} = \frac{2(\eta_{0,\infty} - \alpha_0)}{M^2 - (\eta_{0,\infty})^2} = \frac{2}{3} \quad (46)$$

Equation (46) is equivalent to equation (26). Unlike the inviscid case, the viscid models require distinction between $\eta_{0,crs}$ during constant rate of strain and $\eta_{0,\infty}$ after infinite creep.

This distinction may be illustrated using parameters determined from a CRS K_0 test on organic clay. The parameters are given in Table 3; the adopted constant rate of strain was $6.4 \cdot 10^{-7}$ 1/s. These parameters provide a rather close fit to the measured stresses and strain. The fitted stress path is shown in Fig. 18(a), and the values of $\eta_{0,crs}$ and $\eta_{0,\infty}$ are indicated. In this case, as is usual, the latter is the smaller value, and one-dimensional creep from state B (path I) produces a slight decrease of η_0 and an increase of K_0 . Den Haan (2002) shows that parameter combinations exist such that $\eta_{0,\infty}$ is larger, and then K_0 would decrease during creep from a normally consolidated state.

The slope of the unloading path in Fig. 18(a) along BC quickly tends to $\eta_{0,el}$ as creep rates become small. Eventually failure in extension occurs when M_e is reached. One-dimensional creep following unloading such as paths II and III tend to the $\eta_{0,\infty}$ line, just as path I. Now, however, K_0 decreases. Fig. 18(b) shows that generally, compressive vertical strain occurs, but III initially produces negative creep (0.5% strain). This is due to the large degree of unloading, and the slope of the state surface at the current stress falling below $\eta_{0,el}$. During the creep along III, the state surface rotates strongly downwards, as seen from the development of α in Fig. 18(b). At the point of maximum swelling the tangent to the state surface is equal to $\eta_{0,el}$, as is shown in Fig. 18(a). Rotation then occurs in the opposite direction and on the $\eta_{0,\infty}$ line, its orientation is again in accordance with the initial value. The timescale associated with the creep is large and will not always be of practical concern, but the initial rate of decrease of K_0 is rather high.

Negative creep is known to occur and plays a significant rôle during removal of preloading on soft soils. It occurs after smaller amounts of unloading than predicted by the

Table 3. Properties and ACM parameter values, Markermeerdijk organic clay

Bulk density: kN/m ³	Water content: %	λ^*	κ^*	μ^*	ν'	M_c	ω	ω_d	α_0	p'_{p0} : kN/m ²
13.8	85	0.15	0.017	0.0164	0.22	1.15	20	1.6	0.35	29

Fig. 18. Oedometeric compression and creep for Markermeerdijk organic clay, using ACM: (a) ABC, loading at constant rate of strain (6.4×10^{-7} 1/s) to $\sigma'_v = 150$ kPa followed by unloading to failure in extension; I, II, III, creep at constant σ'_v ; (b) development of strain and anisotropy during one-dimensional creep along paths I, II and III

ACM, and the model is clearly not designed to cope adequately with such negative creep.

The validity of equation (25) (Jaky's rule) for organic soils is now investigated. When $\alpha = 0$ as in the ICM, M can be solved from equation (45), as the remaining parameters can be found from the oedometer test. In the ACM, however, an additional assumption is needed, and this allows the authors to invoke equation (25). The authors then use equation (26) or (46), replacing $\eta_{0,\infty}$ by η_0 . Fig. 19 is an indirect comparison of the M values of a range of organic soils, determined

Fig. 19. Indirect comparison of Cam-clay M parameter for organic Dutch soils, obtained from triaxial tests, from Jaky's equation together with measured $K_{0,nc}$ and from fitting the ICM model to K_0 -CRS oedometer tests

from triaxial compression tests, from Jaky's equation as in the ACM using $K_{0,nc}$ found in CRS K_0 tests, and from the ICM using equation (45) with $\alpha = 0$ and the parameters λ/κ , ν and $K_{0,nc}$ found in the CRS K_0 tests. The measured K_0 values are also shown. All triaxial test samples originated from underneath the crest of a dyke and, being reconsolidated anisotropically to approximately the in situ stresses, can be considered to be normally consolidated or lightly overconsolidated. Jaky's equation grossly underestimates the triaxial M values, whereas equation (45) coincides with the lower triaxial results. The higher triaxial values are of peat and highly organic clay ('Gorcum light', GL), and these values lying above the ICM/ K_0 -CRS values may be an indication of the influence of fibres on the strength of the former. Such influence would be lacking in the oedometer.

In summary, the ACM in its present form may not be applicable to organic clays and peat, while its simpler ICM variant appears to be highly useful in practice, if its parameters are determined from the CRS K_0 oedometer.

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Authors' reply

First of all, we would like to express our gratitude to Den Haan for the interest shown in our paper and for the very interesting data on creep behaviour of peat. However, before we discuss the constitutive behaviour of peat and organic soils, as put forward by Den Haan, we would like to provide some words on 'simple' inorganic clays. From 1950 on, experimental clay data started to become available from all over the world, which has enabled us to work on realistic constitutive models, first for isotropically consolidated kaolin, and later for anisotropically consolidated natural and reconstituted clays. Data on creep and other viscous effects also became available, through the work by Den Haan, among others.

In our paper a new ACM was developed by combining the ideas of Vermeer & Neher (1999) and Wheeler *et al.* (2003). We discussed its merits when comparing its predictive abilities to its isotropic counterpart (ICM), showing its general improvement without dramatically increasing its complexity and, therefore, not hindering the applicability in engineering practice.

ACM is a constitutive model for creep in soft soils, which was developed for normally or slightly overconsolidated clays and silts, based on a body of experimental data on inorganic clays, see for example Wheeler *et al.* (2003), Karstunen & Koskinen (2008) and Yin *et al.* (2010). Those materials obviously share some common features with organic soils, such as the common tendency to show time-dependent behaviour, but on the other hand some divergences too. In developing the ACM model, and the time-independent anisotropic model S-CLAY1 (Wheeler *et al.*, 2003), it was assumed that the initial anisotropy of soft sedimentary clays has developed owing to sedimentation in water followed by one-dimensional consolidation under its own self-weight. It is, however, questionable how well the effect of anisotropy of the matrix and the fibres in organic soils can be represented with the current version of the ACM model. Some of the perceived differences, nicely illustrated in the discussion by Den Haan, are considered here.

The model requires the definition of initial anisotropy, in addition to the soil constants describing the evolution of anisotropy with creep strains. The basic assumption in ACM is the relation between initial anisotropy and lateral earth pressure at rest K_0^{NC} (Leoni *et al.*, 2008). The well-established Jaky's formula can be used as a correlation to estimate K_0^{NC} for inorganic soils, in the normally consolidated region, which has been proven to be valid for a wide range of inorganic soils (Kulhawy & Mayne, 1990). Therefore, based on the estimated or measured value of K_0^{NC} , it is possible to define the initial components of the fabric tensor, provided the soil can be assumed to be cross-anisotropic.

When considering organics soils, such as peat, based on the data in Fig. 19 by Den Haan, Jaky's formula does not hold, which means that the values of K_0^{NC} need to be identified independently, for example based on measurement from K_0 -CRS tests. For peat, the K_0^{NC} values would seem to be very low (see Fig. 19), while in contrast the values of M are apparently very high. Based on equation (26) this would result in a negative α_0 value. This can intuitively be linked to the fabric of organic soils which consists of fibres in addition to a fine-grained soil matrix. Accordingly, the value of ω_d , which controls the rate of evolution of anisotropy due

Fig. 20. Constitutive ellipses of ACM for $M=3.0$ and $K_0^{\text{NC}}=0.5$

to deviatoric creep strains in equation (27), becomes negative (when M is high and K_0^{NC} is low). With the calibration procedure proposed by Leoni *et al.* (2008), the initial anisotropy expressed by the scalar α_0 , is a consequence of assumed K_0^{NC} and M values. Those can be either measured or estimated.

In deriving equation (44), Den Haan has assumed the same K_0^{NC} for the isotropic and anisotropic versions of the model. In the isotropic version of the model, the value of M (relating to the shape of the current stress surface) is a consequence of the choice of K_0^{NC} . This is not true for ACM, as in this case K_0^{NC} and M can be independently chosen, by assuming a suitable value for α_0 (including negative values). Hence, the statement that the ACM 'therefore has substantially lower values of M than the ICM' is incorrect. Fig. 20 shows the shape of constitutive ellipses when $\alpha_0 < 0$, in one-dimensional CRS compression. The material parameter set used for the analysis is given in Table 4.

As for the difference between CRS K_0 and $K_{0,\infty}$ we agree with the comments put forward by Den Haan, but as already pointed out, we wonder whether the small difference between the two values is important from a practical point of view.

In conclusion, Den Haan increased our awareness of the fact that the creep behaviour of peat is different from that of inorganic clays. Before 2000, we had some interesting papers on peat (e.g. Adams, 1965) and later on some journal papers (e.g. Berry & Poskitt, 1965; Den Haan, 1996), but up to now experimental data are still limited. On the other hand, huge peat areas exist in tropical Asia in regions of large population concentrations, and this might trigger further experimental research (Huat *et al.*, 2009) in order to obtain data from a larger variety of stress paths (e.g. triaxial extension) useful for constitutive modelling.

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Table 4. Parameters for CRS simulation

λ^*	κ^*	μ^*	ν'	M_c	ω	ω_d	α_0
0.15	0.017	0.0164	0.22	3.0	80	−2.23	−1.59

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