XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

CREEP MODELLING ACCORDING TO ADACHI-OKA IN PRACTICE
MODELISATION DE FLUAGE SELON ADACHI-OKA EN PRATIQUE

B.A.N. Koehorst ***R.J. Termaat*** ***B.H.P.A.M. The***

Ministry of Public Works and Transport, Road and Hydraulics Division
Delft, The Netherlands

SYNOPSIS: The problem of using the Adachi-Oka formulation in practice is that the final deformation will not be larger than the deformation calculated with the Cam-Clay model. In fact the original Adachi-Oka model is a time dependent Cam-Clay model. To calculate additional creep deformations the model has to be improved. In this paper an "improved" method will be presented. This method has been verified with a one-dimensional analytical compression test and measurements of a prototype test embankment. The results are quite satisfactory, but further research is required.

1 INTRODUCTION

Due to the reconstruction of dikes in the Netherlands a great amount of fill material has been placed on soft subsoil. Because of the low permeability of the subsoil, this loading results in high excess-pore pressures and large settlements. In some cases it seems to be that also creep effects are involved.
For this reason the Dutch Ministry of Public Works, in cooperation with Delft University of Technology and Delft Geotechnics has worked on the implementation of the Adachi-Oka creep model in the FEM code MPLUTO of Delft Geotechnics. In this paper the discussion is focused on the validation of this model. The validation can be divided in two parts: a comparison with analytical solutions for simplified cases and a comparison with field data (Vaasa embankment [1,3]).

In this paper the theory of the Adachi-Oka model is described briefly and is compared with the classical theory. An improvement of the Adachi-Oka model is discussed and verified for a one-dimensional analysis. Finally the calculations for the Vaasa embankment are extended with the 'improved' Adachi-Oka model.

2 THE CLASSICAL THEORY

In this section a short review of the classical formulas of one-dimensional soil behaviour will be given. The parameters used in these formulas will be used in the following sections.

The classical one-dimensional compression theory is a combination of the primary compression formulated by Terzaghi:

$$v_p = v_{p_0} + C_c \log\frac{p+\Delta p}{p} \qquad (1)$$

and the secondary compression formulated by Bjerrum:

$$v_t = v_{t_0} + C_a \log\frac{t}{t_0} \qquad (2)$$

or

$$v_t = v_{t_0} + \frac{C_a}{2.3}\ln\frac{t}{t_0} \qquad (3)$$

t_0 is a reference time. In Dutch engineering practice t_0 = 1 day. The Bjerrum formulation is based on the logarithmic creep theory of Keverling-Buisman (fig. 3).

3 THE ADACHI-OKA MODEL

The model of Adachi-Oka describes the time dependent soil behaviour (creep). This model is a so-called overstress model and is based on the Cam-Clay model. An overstress model means that the viscoplastic strain rate depends on the distance between the stress point and the time-dependent cap. The longer the distance, the larger the viscoplastic strain rate is. When the stress point lies on the cap the viscoplastic strain rate becomes zero; that would mean that the creep process has stopped! This is in fact in contradiction with the definition of creep. At a constant stress level the soil should deform continuously in time. For our application, i.e. drained creep, this is an important limitation. For the original application of Adachi-Oka (undrained behaviour) this limitation was of no importance.

Adachi-Oka uses in this formulation the next flow rule:

$$f_w = \ln\left[\frac{p}{p_c}\left(1+\frac{q^2}{M^2p^2}\right)\right] - \frac{v^p}{(1-n)(\lambda-\kappa)} \qquad (4)$$

and the viscoplastic strain rate was defined as:

$$\dot{\underline{\varepsilon}}^{vp} = \langle \eta e^{m' f_w} \rangle \frac{\partial f_w}{\partial \underline{\sigma}} \qquad (5)$$

with

$$\langle \eta e^{m' f_w} \rangle = \begin{cases} \eta e^{m' f_w} & if\, f_w > 0 \\ 0 & if\, f_w \leq 0 \end{cases} \qquad (6)$$

The two creep parameters are the viscosity η [time^{-1}] and the coefficient m'[-].

4 COMPARISON BETWEEN THE CLASSICAL THEORY AND THE ADACHI-OKA MODEL

To derive a relation between the classical parameters C_c and C_α and the Adachi-Oka parameters m' and η for a one-dimensional situation, the classical theory will be compared with the Adachi-Oka model. For reasons of simplicity we consider a soil without cohesion. We assume that the ratio between the vertical stress and the isotropic stress is constant, i.e. K_0 is constant, which is a reasonable assumption.

$$p = \frac{1+2K_0}{3}\sigma_{yy} \tag{7}$$

The viscoplastic volumetric strain rate according to Adachi-Oka in a one-dimensional situation is:

$$\dot{\varepsilon}^{vp} = \langle \eta e^{m' f_w} \rangle \frac{\partial f_w}{\partial p} \tag{8}$$

Differentiation of the flow rule gives:

$$\frac{\partial f_w}{\partial p} = \frac{[1-\frac{q^2}{M^2p^2}]}{p[1+\frac{q^2}{M^2p^2}]} \tag{9}$$

The viscoplastic volumetric strain rate becomes:

$$\dot{\varepsilon}^{vp} = \frac{\eta}{\mu p} e^{m' \ln \frac{p}{p_t}} \tag{10}$$

with

$$\mu = \frac{[1+\frac{q^2}{M^2p^2}]}{[1-\frac{q^2}{M^2p^2}]} \tag{11}$$

Considering Bjerrum:

$$v_t = v_{t_0} + \frac{C_\alpha}{2,3}\ln\frac{t}{t_0} \tag{12}$$

The viscoplastic volumetric strain rate is found by differentiation:

$$\dot{\varepsilon}^{vp} = \frac{C_\alpha}{2,3(1+e)t_0} e^{\frac{2,3}{C_\alpha}(v_{t_0}-v_t)} \tag{13}$$

When $v_{t_0}-v_t$ (14) is replaced by $\frac{C_c-C_s}{2,3}\ln\frac{p}{p_t}$ (15) then the formulation according to Bjerrum becomes (see figure 1 for explanation):

$$\dot{\varepsilon}^{vp} = \frac{C_\alpha}{2,3(1+e)t_0} e^{\frac{C_c-C_s}{C_\alpha}\ln\frac{p}{p_t}} \tag{16}$$

Comparing Bjerrum (16) and Adachi-Oka (10) the following expressions can be derived:

$$m' = \frac{C_c-C_s}{C_\alpha} \tag{17}$$

and

$$\frac{\eta}{\mu p} = \frac{C_\alpha}{2,3(1+e)t_0} \tag{18}$$

From laboratory tests C_α and t_0 can be determined. Using formula (18) η can now be calculated. In the last equation the left hand side is stress-dependent, which means that the Adachi-Oka model is not 100% analogue to the classical approach.

5 IMPROVEMENT OF THE ADACHI-OKA MODEL

Let us now consider a soil with a preconsolidation pressure p_c. The soil will be subjected to a constant pressure p, time-dependent behaviour will now occur. According to Adachi-Oka time dependent behaviour will stop as soon as the volume corresponds with a volume v_{t_0} at $t=t_0$ (t_0 is a reference time), so creep will stop when the reference time t_0 is reached (see also figure 1).
In other words, the criterion applied in formula 6 means that creep has stopped as soon as (see figure 1):

$$p_t \geq p \tag{19}$$

In the Adachi-Oka model the creep has stopped when the deformation is equal to the primary deformation which is not the reality. Creep has to stop at a specific volume v_{t_∞} that corresponds to $t = t_\infty$, or when $p_t \geq \beta p$ (see figure 1).
The factor β is equal to:

$$\beta = \left(\frac{t_\infty}{t_0}\right)^{\frac{C_\alpha}{C_c}} \tag{20}$$

This relation can simply be derived from figure 1. The meaning of β is a kind of a underconsolidation ratio.

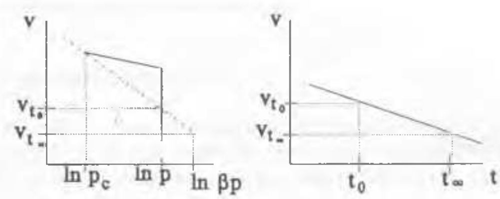

figure 1: v - ln p diagram and v - ln t diagram

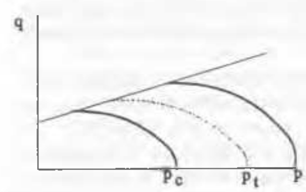

figure 2: p - q diagram

The factor β can be implemented in the yield criterion:

$$\dot{\varepsilon}^{vp} = \langle \eta e^{m' f_w} \rangle \frac{\partial f_w}{\partial \sigma} \tag{21}$$

with

$$\langle \eta e^{m' f_w} \rangle = \begin{cases} \eta e^{m' f_w} & \text{if } f_w > -\ln\beta \\ 0 & \text{if } f_w \leq -\ln\beta \end{cases} \tag{22}$$

By making a calculation with $\beta \geq 1$ it is possible that the specific volume can be bigger than v_{t_0} .

6 COMPRESSION TEST / VERIFICATION

As part of the verification of the FEM code MPLUTO the improved Adachi-Oka model is compared with the analytical solution of an oedometer test. A comparison is made for the vertical displacement and the time at which the creep process has stopped.
The vertical displacement can be calculated with the formula:

$$\epsilon_{yy} = \epsilon^{e} + \epsilon^{p} + \epsilon^{creep} \tag{23}$$

$$\epsilon_{yy} = \frac{C_s}{2,3(1+e)}\ln\frac{p_0+\Delta p}{p_0} + \frac{C_c-C_s}{2,3(1+e)}\ln\frac{p_0+\Delta p}{OCR_0 p_0} + \frac{C_\alpha}{(1+e)}\log\frac{t}{t_0} \tag{24}$$

The time at which the creep process has ended can be calculated with the formula:

$$t_\infty = t_0\left(\frac{p_f}{p}\right)^{\frac{C_c}{C_\alpha}} \tag{25}$$

With MPLUTO three different types of calculations have been made, the Adachi-Oka parameters m' and η have been altered.
In table 1 the parameters are listed.

table 1: list of parameters.

calculation	1	2	3
σ_{yy} [kPa]	100	100	100
$\Delta\sigma$ [kPa]	100	100	100
C_c [-]	0,23	0,23	0,23
C_s [-]	0,046	0,046	0,046
C_α [-]	0,0047	0,0047	0,036
K_0 [-]	0,5	0,5	0,5
1+e [-]	2,27	2,27	2,27
η [Pa/s]	1e-2	1e-3	1e-1
ϕ [°]	38,8	38,8	38,8
M [-]	1,58	1,58	1,58
With (18) t_0 [days]	19	190	14
t_0 [days]	1	1	1
β or OCR_0 [-]	1,07	1,12	1,56

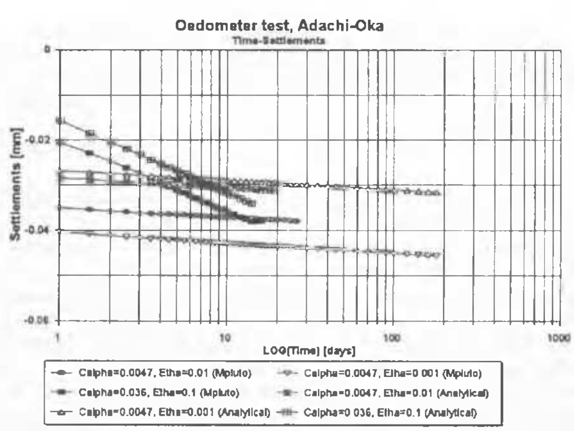

figure 3: oedometer verification

In figure 3 the results of the analytical and numerical calculations are summarized.

7 VAASA TRIAL EMBANKMENT

In the paper presented by A. Näätänen and P. Vepsäläinen et al. predictions have been made for the trial embankment in Vaasa (Finland) [1]. These calculations have been made without a model for the creep behaviour of the soil. By the Dutch Ministry of Public Works and Transport, in cooperation with collegues from Finland, calculations have been made with the Adachi-Oka model. The results were presented at the NUMOG IV conference in Swansea 1992 [3].

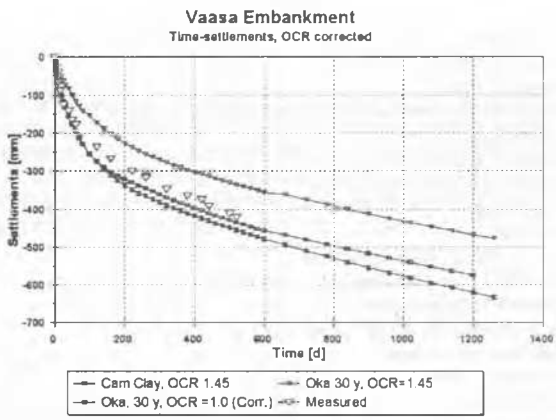

figure 4: simulation of Vaasa embankment

Considering the time-settlement diagram differences between the observed deformation and the calculated deformation have been noticed. Figure 5 summarizes the results. The difference between the Cam-Clay results and the Adachi-Oka results is remarkable and was unexpected. The explanation is that the yield-curve (the cap) reacts time dependent in the Adachi-Oka model and instantaneous in a Cam-Clay calculation. This means that the soil reacts stiffer in the Adachi-Oka model (it takes time to deform). Finally the soil will get the same final deformation as in the Cam-clay calculation and no more! This is due to the fact that the viscoplastic strain rate becomes zero when the stress point is part of the yield curve. So by keeping the effective stress constant, there is no additional deformation. This means that creep is not simulated at all. By making a calculation with an "underconsolidated" material the stresses will always be larger than the stresses belonging to the yield curve. This means there will be additional deformation due to the viscoplastic strain rate. With the "improved" Adachi-Oka model presented in the previous section the parameters can be easily determined. From figure 4 it can be seen that the deformations calculated with the "improved" Adachi-Oka model are now larger than the deformation calculated with the Cam-Clay model.

8 CONCLUSIONS

From the calculations made so far it seems that with the improved Adachi-Oka model creep can be simulated quite well. Additonal deformations due to constant effective-stress level can be generated now. Consequently, the deformations calculated with the improved Adachi-Oka method will be larger than those calculated with the Cam-Clay model. However, further research is required to see whether this new method is suitable for all kinds of situations.

9 LIST OF PARAMETERS

β underconsolidation ratio
C_α coefficient of secondary compression
C_c compression index
C_s swelling index
e void ratio
ϵ_{yy} vertical strain
ϵ^e elastic strain
ϵ^{creep} strain due to creep
ϵ^p plastic strain
$\dot{\epsilon}^{vp}$ viscoplastic volumetric strain rate
η viscosity
f_w flow rule
ϕ angle of internal friction
κ swelling index
K_0 ratio between vertical and horizontal stress in rest
λ compression index
M slope of critical state line
m' creep coefficient Adachi-Oka
μ coefficient
n porosity
OCR_0 underconsolidation ratio
p (applied) isotropic stress
p_c preconsolidation stress
p_t preconsolidation stress during time t
p_0 initial isotropic stress
q deviatoric stress
σ stress tensor
σ_{yy} vertical stress
$\Delta\sigma$ incremental vertical stress
t time
t_0 reference time
t_∞ time at infinity
v_{p_0} specific volume at p_0
v_t specific volume
v_{t_0} specific volume at t_0
v_{t_∞} specific volume at t_∞
v^p cumulative plastic volumetric strain

10 REFERENCES

[1] Vepsalaïnen, P. et al. (1991). The trial embankments in Vaasa and Paimio, Finland. *Proc. of the tenth European conference on soil mechanics and foundation engineering*. Florence, Vol II, pg. 633-640, A.A. Balkema.

[2] Adachi, T. and Oka, F. (dec 1982). Constitutive equations for normally consolidated clay based on elasto-viscoplasticity. *Soils and foundations Vol 22 no 4*. Japanese Society of Soil Mechanics and Foundation Engineering.

[3] Koehorst, B.A.N. and The B.H.P. et al. (aug 1992). The trial embankment in Vaasa, Finland: a simulation with the Adachi-Oka creep model. *Proceedings of the fourth International Symposium on Numerical Models in Geomechanics*. NUMOG IV, Swansea.