An Elasto-viscoplastic Constitutive Model for Swelling Unsaturated Clay

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1. Introduction

Highly expansive soils, such as bentonite are currently considered to be a suitable barrier for isolation of waste, e.g. nuclear, industrial or mining wastes, from surrounding environment. It is important to evaluate the swelling pressure of bentonite imposed on the container and surrounding soils and rocks because of the seepage of groundwater, and the long-term safty of barrier structure itself. In this paper, an internal variable H that reflects the growth of absorption of water into interclay layers is introduced to describe the large volumetric expansive behaviour of microstructure. By adopting this evolutional equation, an elasto-viscoplastic model for unsaturated bentonite is developed based on the elasto-viscoplastic model for unsaturated soil (Oka et al.,2005).

2. Elasto-viscoplastic constitutive model for unsaturated expansive soil

It is assumed that the strain rate tensor consists of the elastic stretching tensor D_{ij}^{e} , the viscoplastic stretching tensor D_{ij}^{vp} and viscoplastic stretching tensor $D_{ij}^{vp(s)}$ caused by microstructural swelling as:

$$D_{ij} = D_{ij}^{e} + D_{ij}^{vp} + \frac{1}{3}\delta_{ij} D_{kk}^{vp(s)} \tag{1}$$

where, $D_{kk}^{vp(s)}$ is a viscoplastic stretching tensor caused by the swelling of microstructure, which is given by

$$D_{ij}^{vp(s)} = -\dot{H} \tag{2}$$

$$\dot{H} = B(A - H) \tag{3}$$

where, H is an internal variable that describes the growth of absorption of water into the interclay layers. A is a parameter for potential of the absorption of water, and B is a parameter controlling the rate of evolution of H.

In this model, the overconsolidation boundary surface and static yield function are defined as follows:

$$f_b = \overline{\eta}_{(0)}^{*} + M_m^{*} \ln \frac{\sigma_m'}{\sigma_{mb}'} = 0 \tag{4}$$

$$f_y = \overline{\eta}_{(0)}^{*} + \tilde{M}^{*} \ln \frac{\sigma_m'}{\sigma_{my}'^{(s)}} = 0 \tag{5}$$

In this study, we assume that the swelling of special mineral units affect the hardening rule as following,

$$\sigma_{mb}' = \sigma_{ma}' \exp\left(\frac{1+e}{\lambda - \kappa} \varepsilon_{kk}^{vp*}\right) \left[1 + S_I \exp\left\{ -S_d \left(\frac{P_i^c}{P^c} - 1 \right) \right\} \right] \tag{6}$$

where ε_{kk}^{vp*} is the viscoplastic volumetric strain taking special swelling effect into account which is defined as

$$\varepsilon_{kk}^{vp*} = \varepsilon_{kk}^{vp} + \gamma |H| \tag{7}$$

where, γ is the parameter which controls the degree of swelling effect on the hardening rule Eq.(6), changing from 0 to 1. γ being equal to 0 means special swelling having no effects on hardening rule, while γ being equal to 1 means maximum swelling having effect on the hardening.

The viscoplastic potential function is given by

$$f_p = \overline{\eta}_{(0)}^{*} + \tilde{M}^{*} \ln \frac{\sigma_m'}{\sigma_{mp}'} = 0 \tag{8}$$

Finally, the viscoplastic stretching tensor is given in the following equation when $f_y > 0$

$$D_{ij}^{vp} = C_{ijkl} \sigma_m \exp\left\{ m' \left(\overline{\eta}_{(0)}^{*} + \tilde{M}^{*} \ln \frac{\sigma_m'}{\sigma_{mb}'} \right) \right\} \frac{\partial f_p}{\partial \sigma_{kl}'} \tag{9}$$

3. Simulation of swelling pressure tests

To investigate the swelling behaviour of bentonite, several swelling pressure experiments with different dry densities and initial degrees of saturation of bentonite (Kunigeru GX) have been carried out by Ono et al.(2006). In this analyses, we have intend to simulate the swelling behaviour of bentonite include the apparent time-softening behaviour by use of finite element method. Fig. 1 shows the finite element mesh and boundary conditions. The bottom is set to be permeable for water

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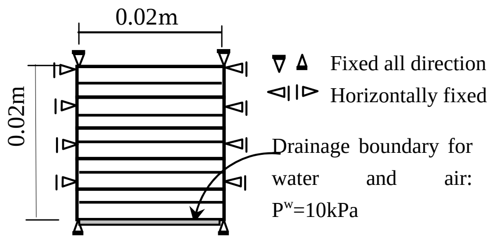


Fig.1 Finite element mesh and boundary conditions

and air by assuming that the water pressure at bottom is 10 kPa and air pressure keeps 0 kPa. A series of analyses have been carried out for different parameters A and γ (see Table 2), other parameters and initial conditions are listed in Table 1. In this analysis, we assumed that

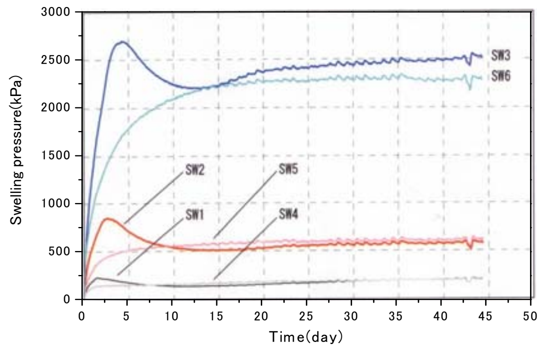
Table 1 Material parameter and initial conditions

Initial suction P^c(kPa)	100
Initial void ratio e_0	0.66
Initial saturation s^w (%)	69.98
Initial water pressure P^w(kPa)	-100
Initial air pressure P^g(kPa)	0
Swelling index κ	0.078
Compression index λ	0.117
Viscoplastic parameter m`	95.4
Viscoplastic parameter C_1(1/s)	9.47×10^{-18}
Viscoplastic parameter C_2(1/s)	9.47×10^{-18}
Stress ratio at critical state M^*_m	0.4736
Suction parameter S_I	0.5
Suction parameter S_d	0.25
Permeability of water at s_r=1 k^W(m/s)	2.0×10^{-11}
Permeability of gas at s_r=0 k^G(m/s)	5.0×10^{-5}
Expansive parameter B	0.00001
Expansive start saturation (%)	75

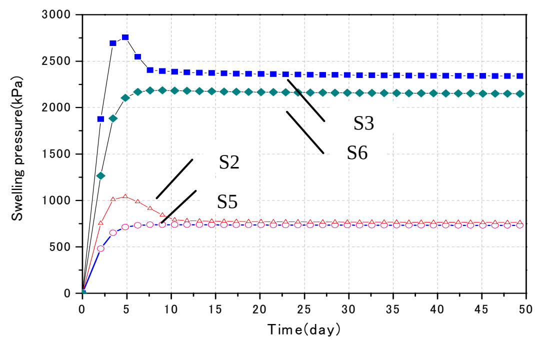
Table2 Parameters for simulation cases

Simulation case	A	γ
S2	0.12	0.1
S3	0.18	0.2
S5	0.10	0.4
S6	0.15	0.4

total suction potential can be divided into two parts, namely, meniscus induced suction and water-absorption induced suction. For the initial suction, we only adopted the meniscus induced one which might be a maximum value for clays. The change of swelling pressure with wetting process in experiments and simulation are shown in Fig .2. From Fig. 2, it is experimentally confirmed that the final swelling pressure increases in proportion to the dry density of bentonite. Simulation results show that Parameter A controls the magnitude of swelling pressure. According to experimental results, for samples with high initial water content, such as SW5 and SW6 (w=21.5% and 15.3%, respectively), swelling pressure increases monotonically, while a time-softening behaviour can be observed in the samples with low initial water content, such as SW2, SW3 (w=6.5 for both). In the simulation, by adjusting the value of parameter γ we can reproduce the similar effects caused by initial water contents.



(a)Experimental results (Ono et al., 2006)



(b)Simulated results by proposed model

Fig. 2 Swelling pressure vs. time

4. Conclusion

Compared with experimental results, it is found that the proposed model can reflect the dry density effect on swelling behaviour. By introducing microstructual swelling, the time-softening behaviour of swelling pressure depending on initial water contents can also be reproduced.

5. Acknowledgement

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6. References

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