Settlement analyses of clays considering soil-water coupling and creep characteristics

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Settlement of clayey soil is one of the most important factors to be considered in the field of geotechnical engineering. Sometimes delayed consolidation and creep settlement are observed in the ground of clayey soil. In this research, settlement analyses of clay are performed using a constitutive model which can consider the effects of density, bonding, time and temperature. The model can explain the strain rate effect, stress relaxation characteristics and creep characteristics of soils comprehensively without fitting the model for a particular phenomenon. The model can also describe other characteristics of soils such as secondary compression, delayed consolidation and consolidation characteristics of naturally deposited soils. Here, settlement of clays has been investigated varying the density of the soil having different states of bonding in soil-water coupled condition.

1. INTRODUCTION

It is known that under one-dimensional consolidation remolded normally consolidated clay shows elastoplastic behavior\(^1\). Remolded clay and natural clay also show time-dependent behavior such as secondary consolidation and strain rate effect. Structured clay exhibits delayed compression\(^2\). Sekiguchi\(^3\), Hashiguchi\(^4\) and other researchers showed the time-dependent behavior of soils in their research works. In this paper, based on the constitutive modeling of geomaterials described in the reference\(^5\) the settlement analyses of clays have been performed.

2. NUMERICAL SIMULATION

Numerical simulations have been carried out using the same parameters of Fujinomori clay which are used in reference\(^5\) are used in these simulations: the compression index \(\lambda\) = 0.1040, the swelling index \(\alpha\) = 0.010, void ratio on NCL \(N\) = 0.830 at \(P_a\) = 98kPa, the parameter for density and confining pressure \(a\) = 100 and the degradation parameter of bonding \(b\) = 40. The initial value of \(a\) for the soil with bonding is \(a_0\) = 0.2. The rate of the plastic void ratio change at reference state is \((\varepsilon - \varepsilon_{pl}) = 1.0 \times 10^{-7}/\text{min}\). Here, the coefficient of secondary compression \(\lambda_s\) is 0.003 unless otherwise stated.

Fig.1 illustrates the results for normally and over consolidated structured soil. Here, the initial void ratios are 0.83 and 0.73, respectively. The initial rate of plastic void ratio change is the same as that at the reference state \((\varepsilon - \varepsilon_{pl}) = 1.0 \times 10^{-7}/\text{min}\). The figure, the solid lines (no creep) show a simulated relation with no time effect. It can be observed that each \(\varepsilon - \log \sigma\) relation for over consolidated structured soils finally approaches the line simulated for normally consolidated soil under the corresponding strain rate. It is also seen that the preconsolidation stress \(p_{c}^0\) increases with increasing strain rates.

One-dimensional soil-water coupled finite element analyses of oedometer tests with instantaneous loading of constant vertical stress were carried out to investigate the consolidation characteristics of clays. Fig.2 shows the finite element mesh for the simulations of oedometer tests, here, drainage was allowed at the top boundary of the sample while the bottom boundary was considered undrained. In order to make the coefficient of consolidation \(c_v\) constant during normal consolidation, regardless of the stiffness of the soil, the following relationship between the coefficient of permeability \(k\) and the current void ratio \(e\) was used: \(k = k_0 \cdot \exp((e - e_{um})/\lambda)\), where, \(e_{um}=0.83\), \(k_0=1.0 \times 10^{-5}\text{cm/min}\) and \(\lambda_0=0.104\), which is the same as the compression index \(\lambda\).

Fig.3 shows the computed \(e - \log \sigma\) simulations of conventional oedometer tests for a NC clay, where the initial stress was \(\sigma_0=98\text{kPa}\) and the instantaneous increment of stress \(\Delta \sigma=98\text{kPa}\) was applied. After applying the stress increment, the consolidation behavior of the soil was investigated for different values of the coefficient of secondary consolidation \(\lambda_s\). The vertical axis \((\varepsilon)\) represents the average void ratio of the soil mass. The solid curve (no creep) represents the results where the effect of secondary consolidation is not considered. A delay in consolidation occurs when the time effect is considered, which shows the creep behavior of the soil. With the increase of the value of \(\lambda_s\), the delay in consolidation becomes more remarkable.

In the cases where the time effect is not much prominent, the curves of void ratio (settlement) versus the logarithm of time have the shape of reverse ‘s’ during the dissipation process of pore water pressure, as is commonly seen in the literature. During secondary consolidation, the slopes of the curves are the same as the coefficients of secondary consolidation \(\lambda_s\) which are employed in the simulations. Fig.4 shows the results of the conventional oedometer tests on the same soil for different models describe in the reference\(^5\). The models produce almost the same shape of the \(e - \log \sigma\) curves.

Fig.5 represents the computed \(e - \log \sigma\) relation for the NC clay with different heights of the sample. The initial condition of

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**Fig.1** Calculated \(e - \log \sigma\) relations under constant strain rates

**Fig.2** FEM mesh (H=1cm)

**Fig.3** Calculated \(e - \log \sigma\) simulation for conventional oedometer tests for a NC clay, where the initial stress was \(\sigma_0=98\text{kPa}\) and the instantaneous increment of stress \(\Delta \sigma=98\text{kPa}\) was applied. After applying the stress increment, the consolidation behavior of the soil was investigated for different values of the coefficient of secondary consolidation \(\lambda_s\). The vertical axis \((\varepsilon)\) represents the average void ratio of the soil mass. The solid curve (no creep) represents the results where the effect of secondary consolidation is not considered. A delay in consolidation occurs when the time effect is considered, which shows the creep behavior of the soil. With the increase of the value of \(\lambda_s\), the delay in consolidation becomes more remarkable.

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each sample was $\sigma_0=98\text{ kPa}$, and the increment of the stress was $\Delta\sigma=98\text{ kPa}$. This figure describes the well-known effects of sample height (e.g., Aboshi, 1973; Ladd et al., 1977). Some time after the load is applied, the consolidation curves for different sample heights converge to a single curve. This tendency of $e$-log curves under different sample heights corresponds to the curve referred to as “Type B” by Ladd et al. (1977). Fig.6 illustrates the $e$-log relation for NC clay with different stress increments ($\Delta\sigma$). The final slope of each curve after the dissipation of the excess pore water pressure is independent of the increment of stress, and is the same as the coefficient of secondary consolidation. The tendency of the computed results has good qualitative correspondence with results of literature.

Fig.3 Simulation of oedometer tests on NC clay

Fig.4 Simulation of oedometer tests on NC clay – comparisons of different models

Fig.5 Simulation of oedometer tests on NC clays: different $H$

Fig.6 Simulation of oedometer tests on NC clays: different $\Delta\sigma$

Fig.7 shows the computed $e$-log response of non-structured and structured clays in normally consolidated and over consolidated states. It is seen that although the behavior of the normally consolidated structured clay (OCR=1.0) is different from that of the normally consolidated non-structured clay under small stress increment, not much difference is noted between them under large stress increment. On the other hand, the behavior of over consolidated clays (OCR=2.9) is highly influenced by the effect of the structure (bonding) not under small stress increments but under large stress increments. Fig.8 shows the computed variations of the excess pore water pressure with elapsed time at the element $\odot$ for structured and non-structured clays. It can be seen from Figs. 7 and 8 that when delayed settlements occur for the structured clay, the pore water pressure, which has almost completely dissipated but has not reached zero, increases again and then decreases to zero. The model describes delayed consolidation regardless of strain softening behavior. It is also noticed that the delayed consolidation occurs when the applied load is close to the apparent preconsolidation stress (see Fig.2).

It can be concluded that the model can explain well the behavior of secondary consolidation of naturally consolidated soil, overconsolidated soil and structured soil.

REFERENCE