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Comparison of Strain Rate-Dependent Consolidation Behaviors of Olga-C Embankment with and without Vertical Drains

배수재 설치 및 미설치 구역으로 구성된 Olga-C 성토지반의 변형률 속도 의존적인 압밀거동 비교

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요 지

본 논문에서는 배수재가 설치된 구역과 설치되지 않은 구역으로 구성된 Olga-C 시험성토지반의 변형률속도 의존적인 압밀거동을 서술하였다. 배수재가 설치된 지반의 압밀거동에 대한 변형률속도의 영향을 해석하기 위하여 응력-변형률-변형률 속도의 관계식($\sigma_v' - \varepsilon_v - \dot{\varepsilon}_v$)을 이용한 축대칭 비선형 점소성 모델을 제안하였다. 제안된 모델은 실험실과 현장의 변형률속도 차이뿐만 아니라 간극수압의 소산과 생성의 복합적인 압밀과정을 고려할 수 있다. 연직 및 반경방향의 배수효과에 의해 배수재가 설치된 지반(Zone B)에서 유발되는 변형률 속도는 배수재가 설치되지 않은 연약지반(Zone A)의 변형률 속도보다 크다. 유발된 변형률 속도의 영향으로 Zone B의 선행압밀하중도 Zone A에서 유발되는 선행압밀하중보다 크다. Olga-C지역의 Zone A에서는 응력완화효과가 유발되지만, Zone B에서는 응력완화효과가 유발되지 않았다.

Abstract

This paper presents consolidation behaviors of soft clay in Olga-C test embankment with and without vertical drains. To analyze effects of strain rate on consolidation of natural clay with vertical drains, axisymmetric nonlinear viscoplastic model for vertical drain was proposed by using a unique effective stress-strain-strain rate relationship $\sigma_v' - \varepsilon_v - \dot{\varepsilon}_v$. The proposed model can consider the difference in strain rate between laboratory and field, as well as combined processes of generation and dissipation of pore pressure during consolidation. The strain rate occurred in drainage-installed deposit (zone B), in which both vertical and radial flows take place, is greater than that occurred in soft clay without vertical drain (zone A). Preconsolidation pressure is larger in zone B than zone A due to the effect of strain rate occurred. Effective stress relaxation occurred in zone A, but not in zone B of Olga-C site.

Keywords : Axisymmetric consolidation, Soft clay, Strain rate, Vertical drain

1. Introduction

Clay exhibits time-and strain rate-dependent behaviors during consolidation process. Strain rate-dependent preconsolidation pressure and time-dependent strain are important characteristics on behavior occurred in soft clay. Preconsolidation pressure and undrained shear strength typically change by 10% per logarithm cycle of strain rate (Leroueil et. al, 1996). As shown in Fig.1, ranges of strain rate occurred in field are very low compared to those usually encountered in laboratory tests (Leroueil et. al, 1988). The strain rate is dependent on the drainage length and characteristics of the clay such as compressibility and coefficient of permeability. The in-situ strain rates occurred

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in soft clay are generally less than about $10^{-9}s^{-1}$. On the other hand, the strain rates occurred in laboratory tests are usually larger than about . $10^{-7}s^{-1}$ One of the main reasons that strain rates occurred in laboratory tests are larger than those occurred in field is that the drainage length is shorter in laboratory sample than field.

The effects of strain rate are also clear in stress-strain curves in Fig. 2. The stress-strain curves followed in the different sub-elements of clay layer vary with the position of the sub-element in the layer or the local strain rate due to the viscous nature of soft clay (Leroueil et al., 1996).

Material parameters obtained from laboratory tests are usually used in numerical analysis to simulate of field behaviors. Laboratory tests are performed in the range of strain rate larger than about $10^{-7}s^{-1}$. But in-situ strain rate is less than about $10^{-9}s^{-1}$. Therefore, it is more reasonable to consider the effects of strain rate for simulations of field behaviors, especially in the case that material parameters obtained from laboratory tests are used in numerical analysis. In order to predict strain rate-dependent behaviors of consolidation on drainage-installed deposits, a theory of axisymmetric nonlinear consolidation was proposed in which considers the variations of compressibility and permeability during consolidation process. A numerical program for the analysis of axisymmetric nonlinear consolidation is developed by adopting finite difference method. It is capable of analyzing consolidation behaviors of multi-layered deposits and simulating time-dependent loading sequence. The results of numerical analysis are compared with field behaviors measured in Olga-C embankment with and without vertical drain.

2. Axisymmetric Nonlinear Viscoplastic Consolidation

A hydrodynamic equation for both vertical flow to drainage boundary and radial flow to central vertical drain can be obtained from the principle of continuity of mass and consideration of Darcy's Law(Lo, 1991; Kim, 1997).

$$-\frac{\partial \varepsilon_v}{\partial t} = \frac{1+e_o}{\gamma_w}\frac{\partial}{\partial z}\left(\frac{k_v}{1+e}\frac{\partial u}{\partial z}\right) + \frac{1+e}{(1+e_o)\gamma_w}\left\{\frac{\partial}{\partial r}\left(k_h\frac{\partial u}{\partial r}\right)+\frac{k_h}{r}\frac{\partial u}{\partial r}\right\} \qquad (1)$$

where t= time; z= depth; r= radius; ε_v= vertical strain; u= excess pore water pressure; e_o, e= initial and current void ratios, respectively; k_v, k_h = coefficients of permeability in the vertical and horizontal directions, respectively, varying with void ratio; γ_w = unit weight of water.

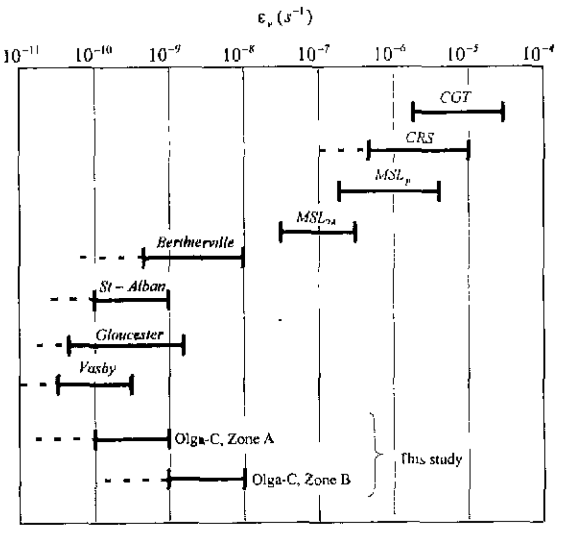


Fig.1 Ranges of strain rates usually occurred in laboratory tests and field (After Leroueil et al., 1988)

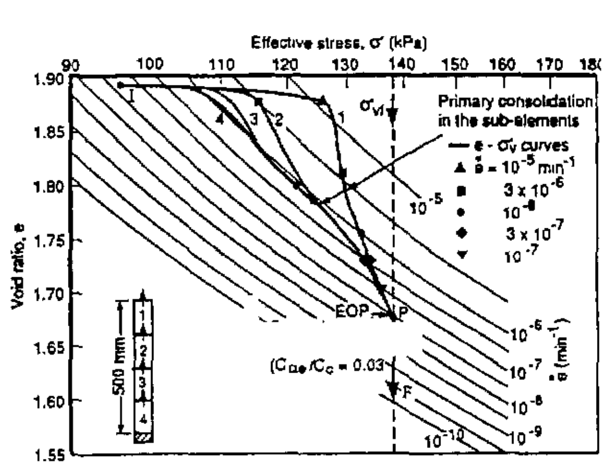


Fig. 2 Consolidation of Saint-Hilaire clay for pressure increment from 97kPa to 138kPa (results from Mesri et al.(1995) reinterpreted by Leroueil and Marques(1996))

any state (σ_v', ε_v) can be expressed as the sum of elastic strain rate ($\dot{\varepsilon}_v^e$), and time-dependent viscoplastic strain rate ($\dot{\varepsilon}_v^{vp}$). The time-dependent viscoplastic strain rate is induced from the stress-strain-strain rate model $\sigma_v' - \varepsilon_v - \dot{\varepsilon}_v$ (Leroueil et al., 1985). The relation of $\sigma_v' - \varepsilon_v - \dot{\varepsilon}_v$ was obtained by various oedometer tests on different natural clays such as multiple stage loading tests with reloading at the end of primary consolidation (MSL_p) and after 24 h(MSL_{24}), constant rate of strain(CRS) tests, controlled gradient tests, and long-term creep tests.

$$\dot{\varepsilon}_v = \dot{\varepsilon}_v^e + \dot{\varepsilon}_v^{vp} \qquad (2)$$

Eq. (3) is the resulting constitutive equation for vertical strain rate. More details can be found in Kim and Leroueil (1999).

$$\dot{\varepsilon}_v = \frac{K}{1+e_o}\frac{\dot{\sigma}_v'}{\sigma_v'} + 10^{[(\log\sigma_v' - \Gamma - \varepsilon_{oi} - C_\varepsilon \varepsilon_v^{vp})/C_p]} \qquad (3)$$

where K = recompression index ($K = C_s/\ln 10$), σ_v'= effective stress, Γ = the value of $\log\sigma_{pc}'$ at = $\dot{\varepsilon}_v^{vp} = 10^0$, C_p= preconsolidation (yielding stress) index, i.e. the slope of $\log\sigma_{pc}'$ against $\log\dot{\sigma}_v^{vp}$. C_ε = compression index, i.e. the slope of $\log(\sigma_v'/\sigma_{pc}')$ versus ε_v^{vp}, and ε_{oi} = intercept. The values of Γ, C_p, C_ε, and ε_{oi} are constants for the given ranges of strain rate and strain, respectively. The value of Γ is dependent on temperature.

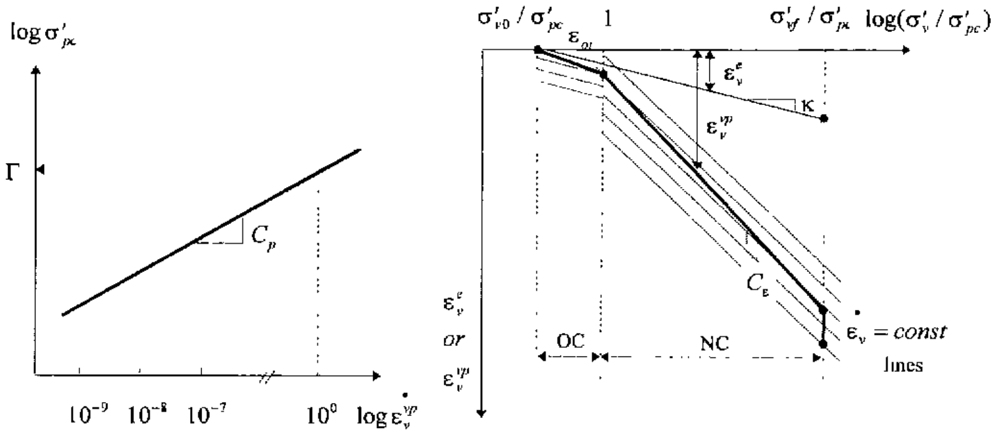
In order to obtain total vertical strain, integrating Eq. (3) with respect to time gives:

$$\varepsilon_v = \int \dot{\varepsilon}_v \, dt \qquad (4)$$

As schematically illustrated in Fig. 3, total strain during consolidation process is the sum of elastic and viscoplastic strain components. Viscoplastic strain takes place in both overconsolidated and normally consolidated regions even though current excess pore pressure is not fully dissipated to zero. Viscoplastic strain is however smaller in overconsolidated region than in normally consolidated region. Preconsolidation pressure is calculated based on the strain rate occurred. Larger strain rate gives larger preconsolidation pressure. During the normally consolidated stage, strain increases almost linearly to $\log\sigma_v'$ with a little steeper slope than $\dot{\varepsilon}_v$= constant line. It can be also seen that the strain rate decreases with increasing strain in normally consolidated stage. After excess pore pressure is reduced to zero, compression is only resulted from viscoplastic strain (secondary compression) under a constant effective stress. Calculation of settlements can be performed using Eq. (4) on the assumption of that lateral deformation is negligible.

In relationship of effective stress, pore pressure and surcharge stress, effective stress is written as;

$$\sigma_v' = \sigma_{vo}' + L - u \qquad (5)$$



(a) $\dot{\varepsilon}_v^{vp} - \sigma_n'$ relation (b) $\sigma_v'/\sigma_n' - \varepsilon_v^{vp}$ relation

Fig. 3 Schematic diagram of nonlinear viscoplastic model in which σ'_{vo} is an initial vertical effective stress, and L and u are respectively surcharge stress and excess pore pressure at any given time. The rate of effective stress change is:

$$\dot{\sigma}'_v = \dot{L} - \dot{u} \qquad (6)$$

The variation of excess pore pressure with time can be induced from Eqs. (1), (3), and (6).

$$\dot{u} = \dot{L} + \frac{(1+e_o)\sigma'_v}{K}\left[\frac{(1+e_o)}{\gamma_w}\frac{\partial}{\partial z}\left(\frac{k_v}{1+e}\frac{\partial u}{\partial z}\right) + \frac{1+e}{(1+e_o)\gamma_w}\left\{\frac{\partial}{\partial r}\left(k_h\frac{\partial u}{\partial r}\right) + \frac{k_h}{r}\frac{\partial u}{\partial r}\right\} + -10^{[\log\sigma'_v\Gamma - \varepsilon_{ei} - C_r\varepsilon_v^{tp})/C_p]}\right] \qquad (7a)$$

$$\frac{\partial u}{\partial t} = \left(\frac{\partial u}{\partial t}\right)_{Loading} + \left(\frac{\partial u}{\partial t}\right)_{Dissipation} + \left(\frac{\partial u}{\partial t}\right)_{Viscoplastic-straining} \qquad (7b)$$

where ,

$\log k_v = \log k_{vo} - (e_o - e)/C_{kv}$,

$\log k_h = \log k_{ho} - (e_o - e)/C_{kh}$. C_{kv} and C_{kh} are slopes of vertical and horizontal permeability lines on $e - \log k_v$ and $e - \log k_h$ planes, respectively.

As expressed in Eq. (7), the variation of excess pore pressure with time is influenced by change in pore pressure due to surcharge loading, dissipation of pore pressure due to combined vertical and radial flows according to Darcy's Law, or generation of pore pressure due to a viscoplastic straining. Relaxation of effective stress takes place in case that amount of pore pressure generation is larger than that of pore pressure dissipation. It is noted above Eq. (7) that, for the case of drainage installed deposits, the dissipation effect of pore pressure due to combined vertical and radial flows is generally greater than the generation effect of pore pressure. Therefore, the effect of stress relaxation is negligible comparing to one-dimensional vertical drainage.

The numerical program takes into account decrease in permeability with void ratio, nonlinear compressibility of stress-strain relation, and time-dependent loading for multistage construction. It also handles variations with depth of initial void ratio, coefficient of permeability, and effective stress.

3. Application to Field Behaviors

3.1 Olga-C Test Site and Embankment

The Olga-C test site is located in 10km North-East of Matagami, about 600km North-West of Montreal. The Olga-C test embankment was built to check performance of wick drains on deposit of soft, sensitive varved clay. The geotechnical profile of Olga-C is shown in Fig. 4. Under about 0.5m of peat is varved clay deposit approximately 14m thick. Surface clay was weathered and oxidized to depth of at least 2m. Soft deposit consists of varved clay to depth of 14m, underlain by dense silt and sand. Varves are rather regular, especially between 7m and

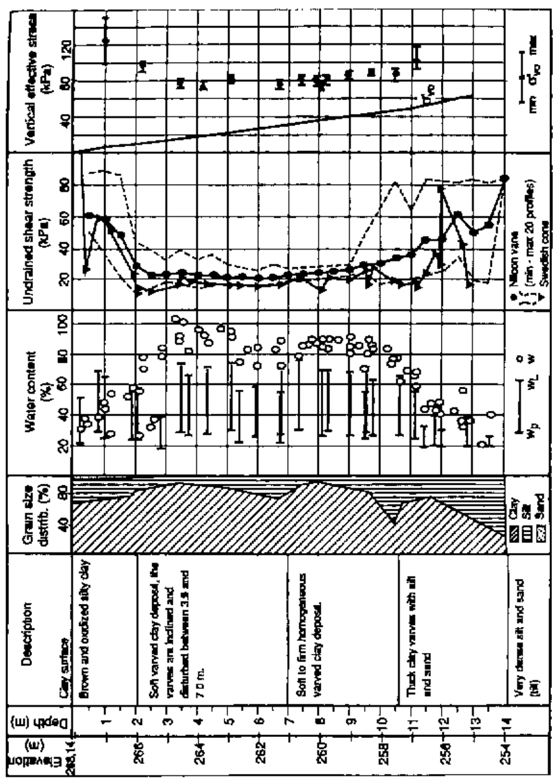


Fig. 4 Geotechnical profile of Olga-C embankment (after Hydro-Quebec-Lavalin, 1991)

Fig. 5 Section of Olga-C embankment

Table 1. Material properties of Olga-C embankment

Layer	Depth (m)	e_o	C_s	k_{vo} (m/sec)*	k_{ho}/k	C_{kh}/C_{kv}
#1	0−2	1.45	0.01	4.0×10^{-9}	1.0	0.60
#2	2−4	2.31	0.01	4.0×10^{-9}	1.0	1.20
#3	4−6.5	2.47	0.01	4.0×10^{-9}	1.25	1.35
#4	6.5−9	2.32	0.01		1.25	1.20
#5	9−11	2.35	0.01	4.0×10^{-9}	1.25	1.25
#6	11−13	1.15	0.01	4.0×10^{-9}	1.25	0 40
#7	13−14	0.85	0.01	4.0×10^{-9}	1.25	0.20

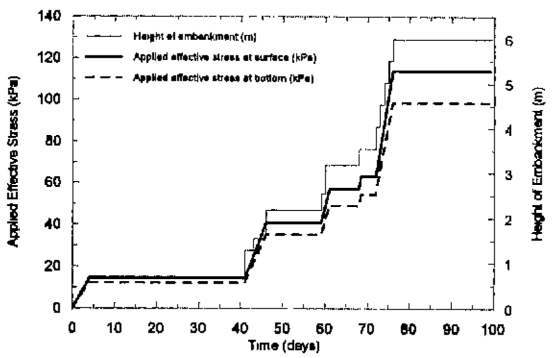


Fig. 6 Height of embankment and applied effective stress

10.5m. At depths between 2 and 7m, the average vane shear strength slightly decreases with depth from 27 to 20kPa; the preconsolidation pressure also decreases from 96 to 75kPa; the plasticity index typically equal to 45 and the liquidity index varies between 1.15 and 1.5. At larger depths and up to 10m, both the undrained shear strength and the preconsolidation pressure slightly increase with depth. At depths larger than 10.6m, the plasticity index is much lower and the undrained shear strength rapidly increases.

The Olga-C test embankment with height of 6m is 50m in top length and 10m in top width. Fig. 5 illustrates the geometry of the test embankment. The observations made during construction and the following two years are described by St-Arnaud et al.(1992). The test embankment was built with four different zones in 1990 (Lavallee et al., 1990): Zone A had no drain; Amerdrain vertical drains were installed in zone B with a spacing of 1.5m and in zone C with a spacing of 1.0m; Alidrain vertical drains were used in zone D with a spacing of 1.0m. All vertical drains were installed in triangular pattern. In this study, zones A and B were chosen to compare field behaviors of soft clay with and without drain.

3.2 Comparison of Calculated and Measured Behaviors

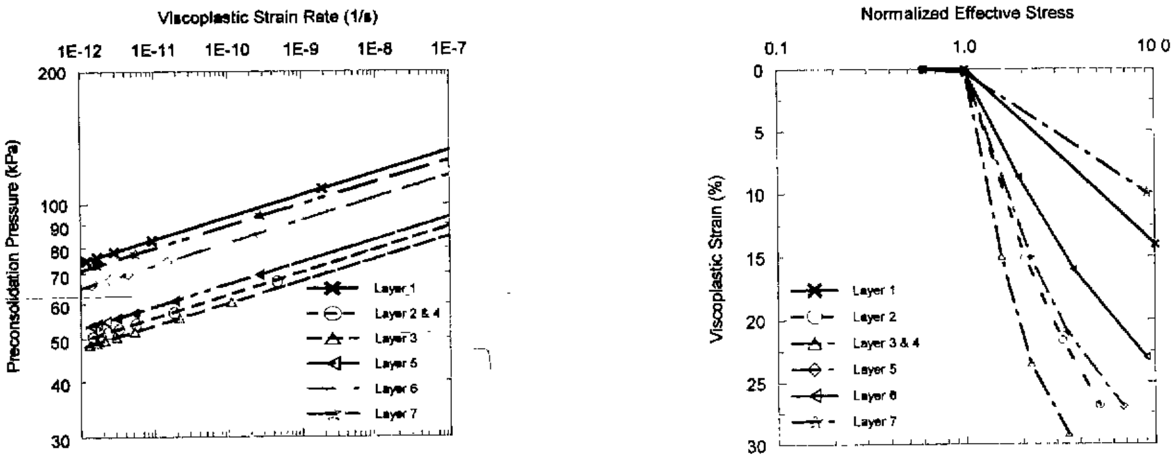
Fig. 6 shows applied effective stresses with time, which simulate surcharge load on soft clay at Olga-C site. Embankment fill has been placed up to 6 m for 76 days. Unit weight of fill is 20.4 kN/m^3. The total applied stress due to fill of 6m is about 122.4 kPa at the base of embankment. The water table rose up 0.8m in embankment fill after construction of embankment of about 45day, leading to a change in the effective stress applied to foundation (St-Arnaud et al., 1992). The applied effective stress is reduced to about 114 kPa at the base of embankment. The effective stress distribution under the deposit was determined using Osterberg(1957) solution, and the effect of partial submergence of the embankment was taken into account as settlement occurs.

The site was divided into 7 layers. The material parameters for numerical analysis are shown in Table 1. Preconsolidatio pressures were measured in 24 hours conventional oedometer tests at 20°C. Coefficients of permeability were measured at the field and the tempera

ture in field was about 7°C. The permeability change index is taken as 0.5 e_o, as generally observed by Tavenas et al.(1983) for soft clay.

Both radial flow to vertical drain and vertical flow to boundary are taken into account in axisymmetric consolidation. On the other hand, only vertical flow is considered in one-dimensional consolidation. For one- dimensional consolidation, a nonlinear viscoplastic model was applied, in which the stress-strain-strain rate model consideringthe effects of strain rate was used (Kim and Leroueil, 1999).

The graphs for relation of ε_v^{vp} - log σ_p' and $\log(\sigma_p'/\sigma_p')$ - ε_v^{vp} are shown in Fig. 7, which were obtained by oedometer tests such as MSL_p and MSL_{24}, or CRS. In order to consider the effect of temperature on preconsolidation



(a) $\varepsilon_v^{vp} - \sigma_p'$ relation

(b) $\sigma_v' / \sigma_p' - \varepsilon_v^{vp}$ relation

Fig. 7 $\dot{\varepsilon}_v^{vp} - \sigma_p'$ and $\sigma_v'/\sigma_p' - \varepsilon_v^{vp}$ relagions for Olga-C embankment

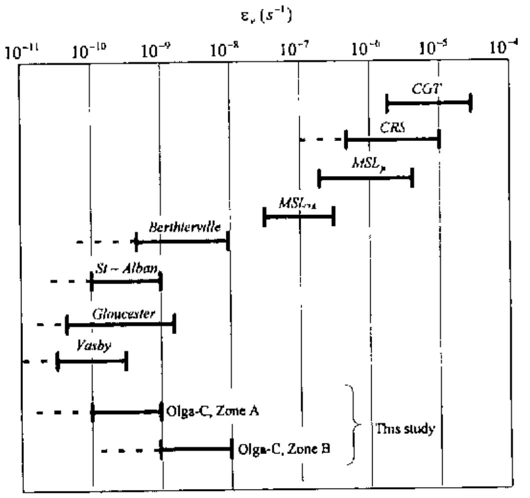


Fig. 8 Dissipation of excess pore pressure with Time

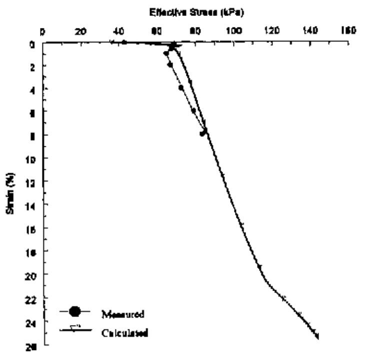
pressure, in-situ preconsolidation pressures at field temperature of about 7°C were increased by 10% compared to the preconsolidation pressures measured in laboratory at 20°C.

The calculated dissipation curves of excess pore pressure in zones A and B are presented in Fig. 8, together with measured excess pore pressures. The calculated dissipation curves of excess pore pressure are good agreement with measured ones. Excess pore pressures more rapidly decrease in zone B with vertical drain than zone A without vertical drain. The excess pore pressure in zone B was reduced to zero after about 1000days, but about 10000days in zone A. Radial flow toward vertical drain is efficient in drainage-installed deposit, reducing consolidation duration to reach a required degree of consolidation.

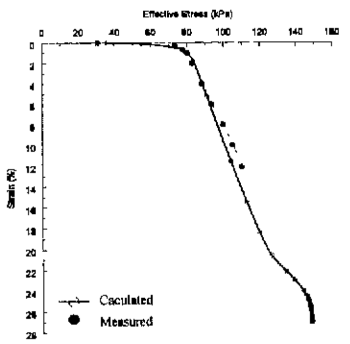
Fig. 9 shows the effective stress-strain relations in zones A and B. There is effective stress relaxation in soft clay without vertical drain, but not in drainage-installed deposit. For the case of zone A, the effective stress decreased (about 5 *kPa*) after in-situ effective stress was approached to the preconsolidation pressure, with pore pressure generation due to viscoplastic strain larger than what can be dissipated according to Darcy's Law. For zone B, effective stress relaxation does not take place due to the dissipation of pore pressure from combined vertical and radial flows is greater than the generation of pore pressure.

As shown in Fig. 9, preconsolidation pressures occurred in in-situ are about 70 *kPa* in zone A and 80 *kPa* in zone B, respectively. In-situ preconsolidation pressure is about 14% larger in zone B than zone A. This means that strain rate occurred in drainage-installed deposit is larger than that of zone A without vertical drain, as shown in Fig. 1. The strain rates occurred in zone A and B are less than about $10^{-9} s^{-1}$ and $10^{-8} s^{-1}$, respectively. The strain rate occurred in drainage-installed deposit after the end of construction, in which both vertical and radial flows take place, is 10 times greater than that occurred in soft clay without vertical drain.

Fig. 10 shows the variations of strain rate with time in zones A and B. It is noted that strain rate decreases with



(a) Zone A without vertical drain



(b) Zone B with vertical drain

Fig. 9 Stress-strain relations in Olga-C test embankment

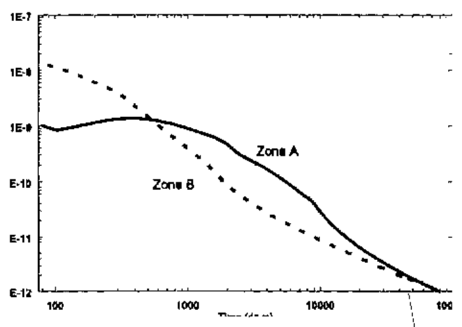


Fig. 10 Variations of strain rate with time in zones A and B

time. Stain rate in zone B more rapidly decreases than zone A, which corresponds to variation of pore pressure with time.

4. Conclusions

To predict strain rate-dependent behaviors during consolidation process on drainage-installed deposits, a theory of axisymmetric nonlinear consolidation was proposed in which considers the variations of compressibility and permeability during consolidation. The proposed model can consider effects of strain rate on consolidation to take into account the difference of strain rate between laboratory and field. This model was applied to simulate the behavior observed in Olga-C embankment. Results show that the model can predict relatively well the observed behavior of soft clay.

For the case of Olga-C embankment, the strain rate occurred in drainage-installed deposit(zone B) after the end of construction is 10 times greater than that occurred in zone A without vertical drain. The value of preconsolidation pressure is 14% larger in zone B than zone A due to the effect of strain rate occurred. Effective stress relaxation occurred in zone A, but not in zone B in which both vertical and radial flows take place.

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