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TIME TO THE END OF PRIMARY CONSOLIDATION (EOP) OF SOFT CLAYEY SOILS: CONCERNING THE EFFECT OF ATTERBERG'S LIMIT AND CYCLIC LOADING HISTORY

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Abstract. In order to observe the end of primary consolidation (EOP) of cohesive soils with and without subjecting to cyclic loading, reconstituted specimens of clayey soils at various Atterberg's limits were used for oedometer test at different loading increments and undrained cyclic shear test followed by drainage with various cyclic shear directions and a wide range of shear strain amplitudes. The pore water pressure and settlement of the soils were measured with time and the time to EOP was then determined by different methods. It is shown from observed results that the time to EOP determined by *3-t* method agrees well with the time required for full dissipation of the pore water pressure and being considerably larger than those determined by Log Time method. These observations were then further evaluated in connection with effects of the Atterberg's limit and the cyclic loading history.

Keywords: Atterberg's limit; cyclic shear; end of primary consolidation (EOP); oedometer test; pore water pressure; settlement

1 Introduction

As a basic problem in the field geotechnical and foundation engineering, the time for separating primary consolidation due to the dissipation of pore water pressure from secondary consolidation has received much attention and extensively clarified through experimental works [1] and numerical researches [2]. This is partly because prediction of consolidation degree and its corresponding settlement of soil deposits is important both for laboratory measurement and the management in construction field. When cohesive soils are subjected to cyclic loading, considerably high accumulation of pore water pressure has been confirmed [3], resulting in structural disturbance and additional settlement to the soils [4]. The consolidation characteristics of clays under cyclic loading have been evaluated based on various testing models and equipments such as cyclic triaxial test [5], uni-directional cyclic shear test [6], repeated

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consolidation test [7] or separate-type consolidometer [8]. Meanwhile, the effect of the cyclic shear direction on such related properties has just observed in recent researches [3,9] and therefore needed further study when promoting for practical application.

Cohesive soil is commonly composed of high portion of silty and clayey fractions which importantly govern the complicated dynamic behavior of the soil. By using relatively large number of cyclic shear tests on both cohesive and cohesionless soils, Vucetic and Dobry [10] indicated that the plasticity index (I_p) is one of the most important index properties contributes the dynamic behavior of cohesive soils. Recently, by using series of cyclic simple shear tests with various cyclic shear directions on clays with a wide range of Atterberg's limits, Nhan et al. [3] have clarified the significant effect of the soil plasticity on its dynamic behaviors. Since the Atterberg's limit of cohesive soil is one of common index properties in most geotechnical application and can be easily observed by simple testing procedures in laboratory, this property should be used under incorporation and correlation when evaluating the dynamic properties of fined-grained soil deposits [10].

In this study, reconstituted specimens of soft clayey soils at different Atterberg's limits were used for oedometer test, pre-consolidation test before undrained cyclic shear and recompression test after the cyclic shear. The settlement and the pore water pressure dissipation during the tests were measured with time and based on which, the time to EOP was determined by different methods and the effect of the Atterberg's limit on this property was then clarified in combination with those induced by different cyclic loading conditions.

2 Experimental and calculation aspects

2.1 Experimental aspects

As an important parameter in the field of soil mechanics, the end of primary consolidation has been studied extensively and methods for determining the time to EOP have been widely developed. Standard oedometer test which is the most common method for determining the consolidation characteristics of cohesive soil was firstly used in this study. The oedometer test was run under loading increment of $\Delta\sigma'_v$ = 0.25 kgf/cm^2 (σ'_v = 0.25 ÷ 0.50 kgf/cm^2) and $\Delta\sigma'_v$ = 0.50 kgf/cm^2 (σ'_v = 0.50 ÷ 1.00 kgf/cm^2) and adapted to Vietnamese standard [11] follow which, testing preparation and measurement procedures are mostly similar to those of Japanese and American standards [12,13]. Pre-consolidation test, undrained cyclic shear test and post-cyclic recompression test with pore water pressure measurement were secondly applied by using the multi-directional cyclic simple shear test apparatus developed at Yamaguchi University (Japan) and widely used in previous researches [2,9,16].

Table 1. Average index properties of tested samples

Property	**Silty sands**	**Silty clays**	**Clayey soils**
Clay content (%)	7.9	19.3	32.4
Specific gravity, G_s	2.68	2.69	2.69
Liquid limit, w_L (%)	20.4	34.6	50.0
Plastic limit, w_P (%)	13.7	15.7	25.4
Plasticity index, I_p	6.7	18.9	24.6

In this study, three kinds of soft-organic soils were used as testing materials. The soils were collected from boreholes along the coastal plains in Central region of Vietnam. The soils were then dried under atmosphere temperature being lower than 60^o to preserve its natural characteristics (especially grain size and organic content) before transporting to Japan as dried powders. Average index properties of used samples are shown in Table 1. Since the soil samples were collected from different boreholes and the index properties in Table 1 are shown as average values, the name of three soil samples should be simply called as "silty sands", "silty clays" and "clayey soils.

Table 2. Conditions for undrained cyclic shear test

Consolidation stress, σ'_{vo} (kgf/cm^2)	Frequency f (Hz)	Number of cycles, n	Shear strain amplitude, γ (%)	Cyclic shear direction
0.50	0.50	200	0.1 , 0.2 , 0.4 , 0.6 , 0.8 , 1.0 , 2.0	Uni-direction and multi-direction with the phase difference of θ = 45^o and 90^o

All experiments were carried out on remoulded specimen with initial state as a slurry at water content of about 150% w_L. For the pre-consolidation test, undrained cyclic shear test and post-cyclic recompression test with pore water pressure measurement, the slurry of each soil was de-aired in the vacuum cell and the saturation of specimen was confirmed as B-value > 0.95 (by applying the load increment to specimen under undrained condition, the pore water pressure was measured and the B-value is defined by the ratio of such pore water pressure to the applied load increment). Such testing method and procedures have been widely applied and can be referred more in detail in different researches related to the dynamic behaviours of clays and sands [3,6,9]. Conditions for the undrained cyclic shear tests were shown in Table 2.

2.2 Calculation of the time to EOP

Based on measurement of the settlement with time, two calculation methods were used for determining the time to EOP. In Fig. 1a, the so-called Log Time method proposed by Casagrande [14] is shown. Firstly, the vertical settlement in strain (ε_v, %) was plotted against the time on a log scale and such a ε_v-log$t$ curve theoretically shows *S*-shaped curve. The second step was to find the starting point of consolidation and one of easiest ways is to refer the settlement corresponding to the start of consolidation by using Square Root of Time method [15]. Thirdly, a tangent line to the steepest segment of the curve, which can be defined by several good data points, was drawn. The next step was to draw the second tangent line following the long-term segment of the ε_v-log$t$ curve. Intersection of two tangent lines represents the time to EOP, symbolized as $t_{LT\text{-}rec}$ and $t_{LT\text{-}pre}$ for specimen with and without cyclic loading history.

The second calculation method is named as *3-t* method. In many cases, the time to EOP determined by the Log Time method mostly becomes underestimated compared with the time for completed dissipation of pore water pressure and in such situations, the *3-t* method is as an effective solution [15]. In this method, the ε_v-log$t$ curve and the tangent line to its steepest section are similar to those used for the Log Time method. The tangent line was then copied as a parallel line by a factor of three times larger in time (Fig. 1b). Intersection of this shifted line and the ε_v-log$t$ curve is defined as the completed dissipation of the pore water pressure in specimen, *i.e.* the time to EOP. The time to EOP determined by *3-t* method was symbolized as $t_{3T\text{-}rec}$ and $t_{3T\text{-}pre}$ for specimen with and without cyclic loading history, respectively.

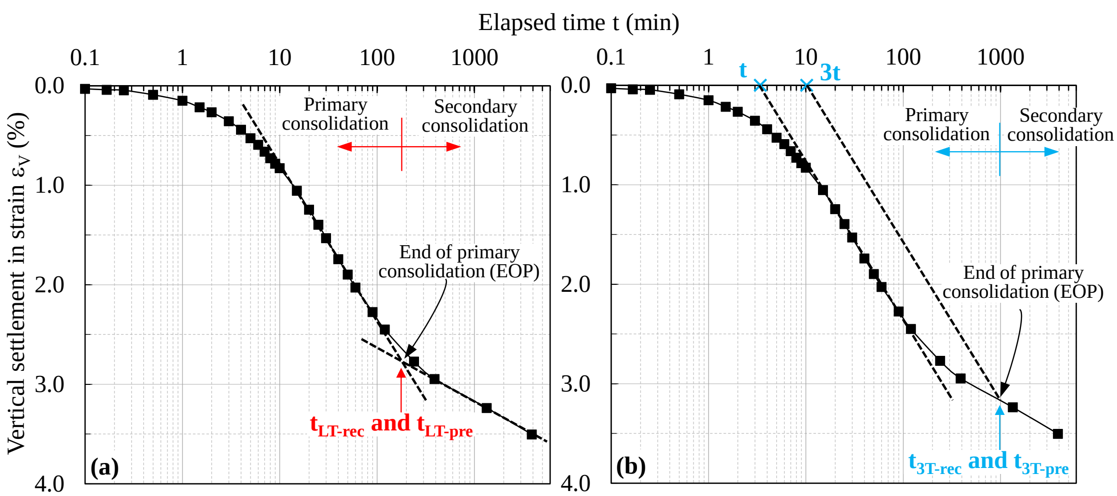


Fig. 1. (a) Log Time method and (b) *3-t* method for determining the time to EOP

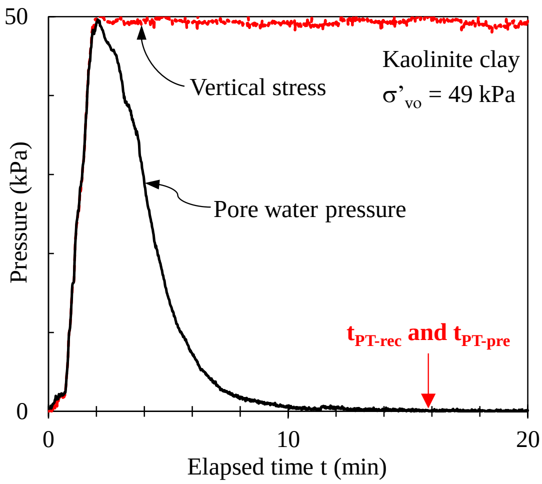


Fig. 2. Typical example for determining the time to EOP by using record of the pore water pressure [16]

In Fig. 2, records of the pore water pressure and vertical stress during the pre-consolidation test are typically shown for Kaolinite clay [16]. Under undrained condition, the pore water pressure in saturated specimen increases with the applied vertical stress. Thereafter, the vertical stress was kept as constant consolidation stress (σ_{vo} = 49 kPa) and the pore water pressure dissipates with the consolidation process. The end of primary consolidation in this case is defined at the time required for full pore water pressure dissipation (*i.e.* the pore water pressure equals zero) which is respectively symbolized as $t_{PT\text{-}rec}$ and $t_{PT\text{-}pre}$ for specimen with and without cyclic loading history. The time required for full dissipation of the pore water pressure is considered as a criterion for EOP both in laboratory measurements and *in-situ* construction management.

3 Experimental Results

3.1 The time to EOP of clayey soils without cyclic loading history

The time to EOP based on the settlement measurement

In this study, in order to prepare specimen for oedometer tests, saturated slurry of each soil was firstly consolidated under the loading increments of $\Delta\sigma'_v$ = 0.1, 0.2, 0.3 and 0.4 kgf/cm^2. Thereafter, soil specimens were unloaded and then were used for oedometer tests under two loading increments of $\Delta\sigma'_v$ = 0.25 kgf/cm^2 (σ'_v = 0.25 ÷ 0.50 kgf/cm^2) and $\Delta\sigma'_v$ = 0.50 kgf/cm^2 (σ'_v = 0.50 ÷ 1.00 kgf/cm^2). Observed results of the settlement in strain (ε_V, %) are plotted against elapsed time in Fig. 3 ÷ 5 for the soils used in this study. Evidently, the settlement increases with the load increment and under the same loading increment, the soils with higher Atterberg's limit show larger settlement.

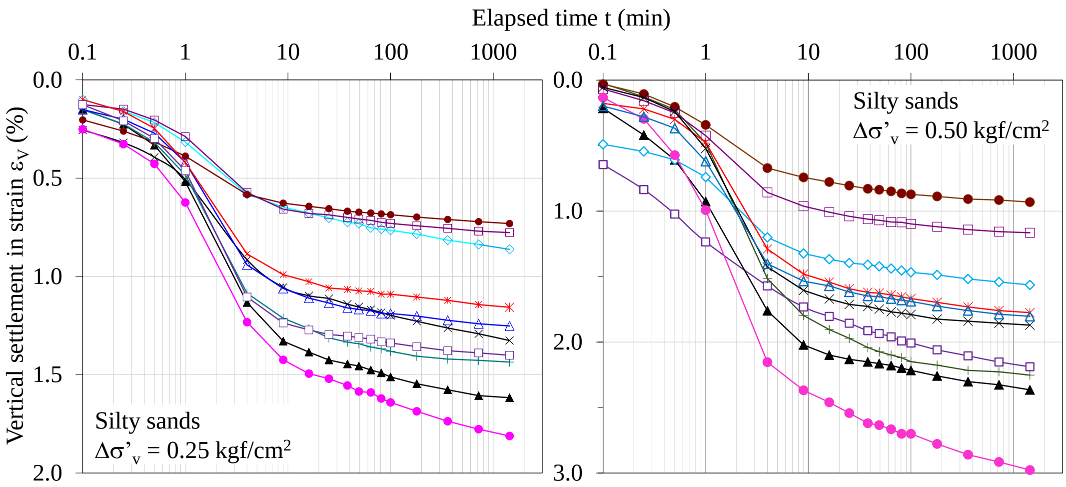


Fig. 3. Vertical settlement versus elapsed time of silty sands under $\Delta\sigma'_v$ = 0.25 and 0.50 kgf/cm²

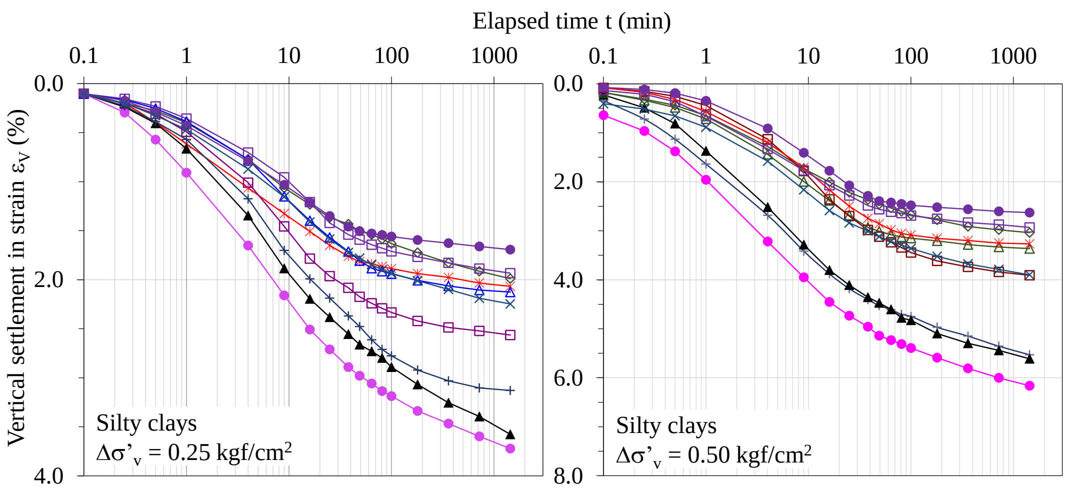


Fig. 4. Vertical settlement versus elapsed time of silty clays under $\Delta\sigma'_v$ = 0.25 and 0.50 kgf/cm²

Based on the observations in Fig. 3 ÷ 5, the time to EOP was then determined and symbolized as $t_{LT\text{-}pre}$ and $t_{3T\text{-}pre}$ for the Log Time method and 3-*t* method, respectively. $t_{LT\text{-}pre}$ and $t_{3T\text{-}pre}$ are considered as the time to EOP of the soils without subjected to cyclic loading history. Obtained values of $t_{LT\text{-}pre}$ and $t_{3T\text{-}pre}$ are plotted against the plasticity index (I_p) in Fig. 6a and 6b for different loading increments. In these figures, solid and dashed lines are fitting lines showing correlations between the time to EOP and I_p for the case of specimen without cyclic loading history.

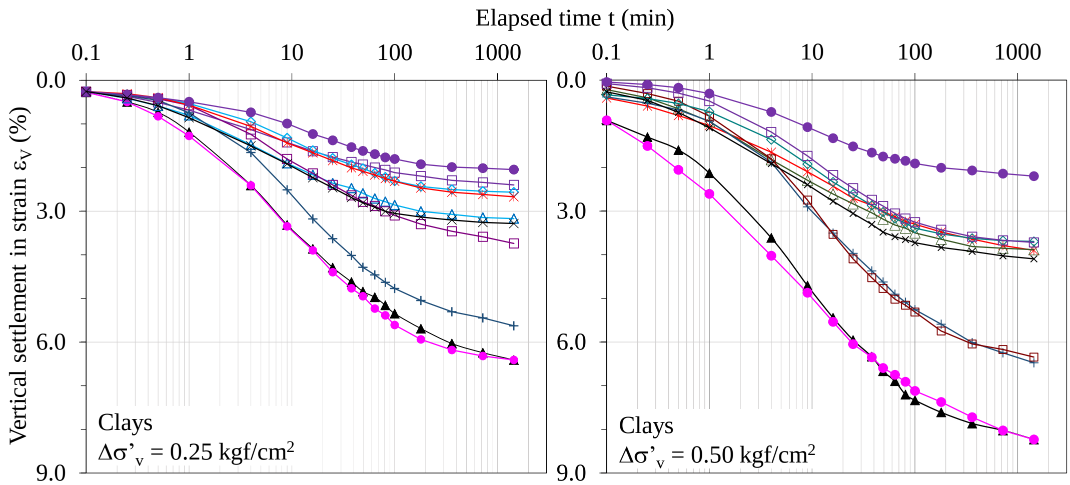


Fig. 5. Vertical settlement versus elapsed time of clays under $\Delta\sigma'_v$ = 0.25 and 0.50 kgf/cm²

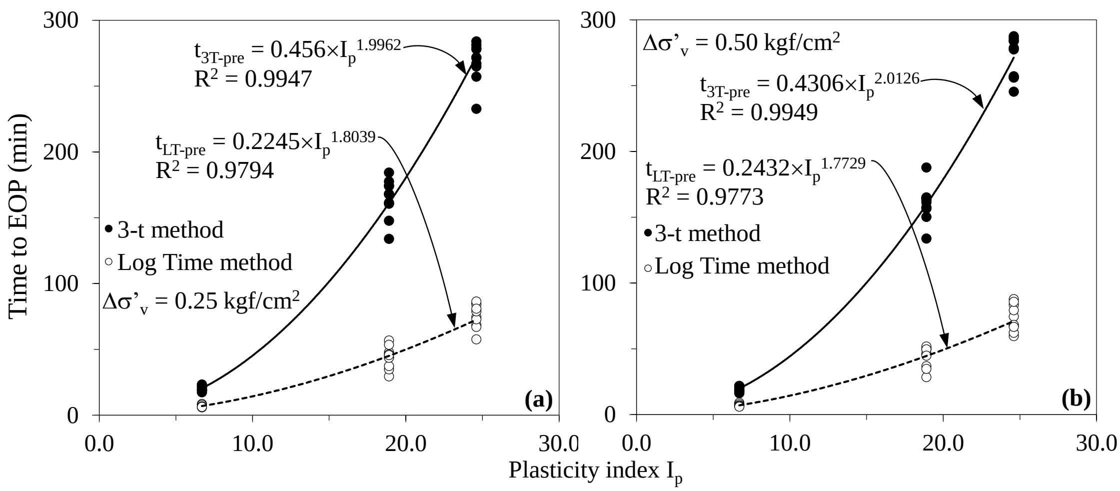


Fig. 6. Relations of $t_{LT\text{-}pre}$ and $t_{3T\text{-}pre}$ versus I_p obtained for different loading increments

The time to EOP based on the pore water pressure measurement

Typical records of the pore water pressure during the pre-consolidation tests before undrained cyclic shear are shown in Fig. 7 for different clayey soils used in this study. The consolidation stress used for the tests was fixed as σ'_{vo} = 0.50 kgf/cm² and under the undrained condition, the pore water pressure which was measured at the bottom surface of specimen, rapidly increases and approaches to σ'_{vo}. Thereafter, drainage was permitted and the pore water pressure was dissipated from the top surface and the soils were consolidated. The time at which the pore water pressure fully dissipates is defined as the time to EOP determined by the pore water pressure dissipation of specimen without cyclic loading history (symbolized as $t_{PT\text{-}pre}$).

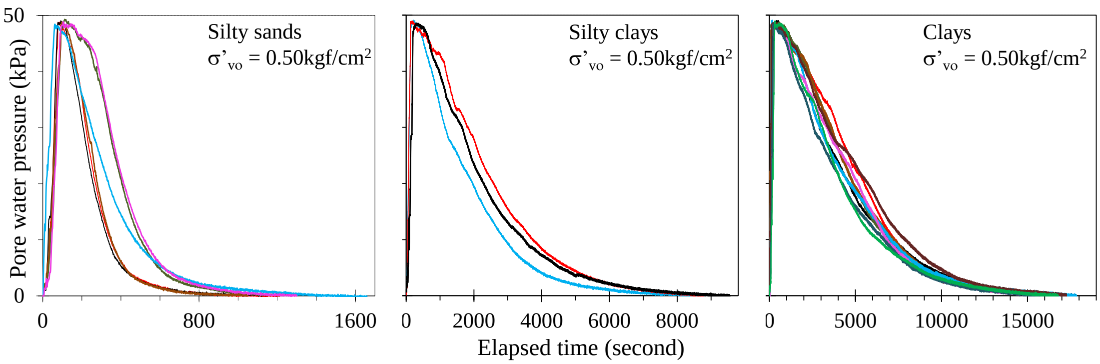


Fig. 7. Typical records of pore water pressure dissipation during pre-consolidation tests on silty sands, silty clays and clayey soils

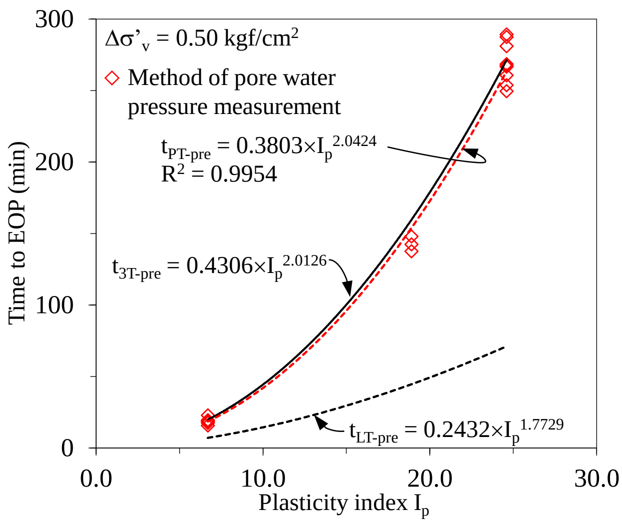


Fig. 8. Relations between the time to EOP determined by different methods and I_p for clayey soils without subjected to cyclic loading history

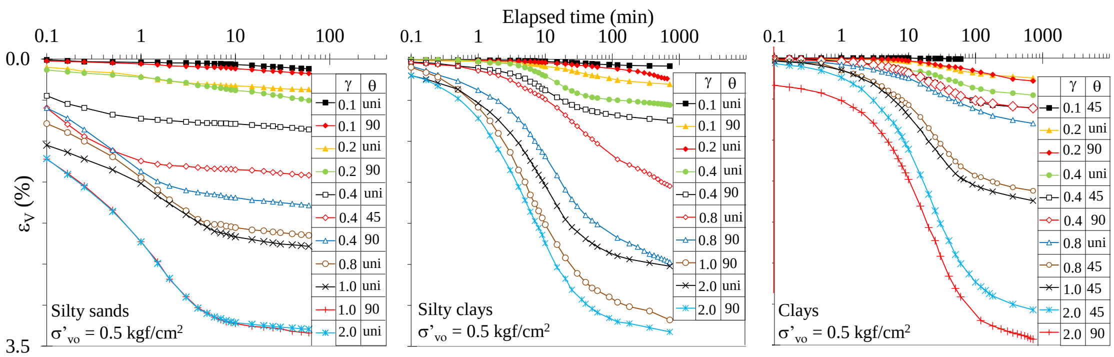
The changes in $t_{PT\text{-}pre}$ with I_p are shown in Fig. 8, in which obtained correlations of $t_{3T\text{-}pre}$ and $t_{LT\text{-}pre}$ versus I_p are also shown by black solid and dashed lines for the same load increment (*i.e.* $\Delta\sigma'_v$ = 0.50 kgf/cm²). It is seen that $t_{PT\text{-}pre}$ increases with I_p and that $t_{PT\text{-}pre}$ reasonably agrees with $t_{3T\text{-}pre}$ and being considerably larger than $t_{LT\text{-}pre}$. Germaine and Germaine [15] indicated that under small stress increments in both oedometer test and shear test, it is usually impossible to determine the end of primary consolidation by using the Root Time method and the Log Time method. In such cases, the 3-*t* method can be used an effective solution because the results obtained by this method agree well to those required for completed dissipation of the pore water pressure [16]. The 3-*t* method has been widely applied in International standard and manual for soil mechanics and geotechnical laboratory measurements [12,15] and therefore, this method should be introduced and applied in Vietnam.

3.2 The time to EOP of clayey soils subjected to cyclic shear

After the pre-consolidation is completed, soil specimen was subjected to undrained cyclic shear conditions as summarized in Table 2. Consequently, the pore water pressure in saturated specimen is generated and accumulated with the application process of the undrained cyclic shear. Following the undrained cyclic shear, drainage was allowed from the top surface of specimen and the settlement and the pore water pressure were then measured with time.

The time to EOP based on the settlement measurement

In Fig. 9, the settlements in strain which is defined as ratio of the settlement to initial heigh of specimen (ε_V, %) in the recompression stage after undrained cyclic shear are shown for different clayey soils. It is seen that the post-cyclic settlements increase with the shear strain amplitude and at the same shear strain amplitude, the settlements induced by multi-directional cyclic shear are larger than those induced by the uni-directional one.



γ is shear strain amplitude (%);
θ is phase difference: "uni" means uni-direction, "45" and "90" mean multi-direction at $\theta = 45^o$ and 90^o, respectively.

Fig. 9. Settlement-time relations of clayey soils in recompression stage after undrained cyclic shear

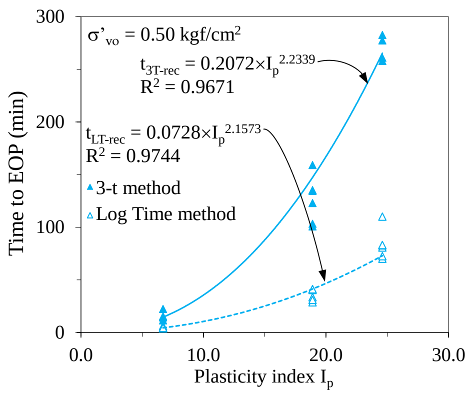


Fig. 10. Relations of $t_{LT\text{-}rec}$ and $t_{3T\text{-}rec}$ versus I_p obtained for clayey soils pre-subjected to cyclic shear

By using observed results in Fig. 9, the time to EOP was determined and denoted as $t_{LT\text{-}rec}$ and $t_{3T\text{-}rec}$ for the Log Time method and *3-t* method, respectively. Obtained values of $t_{LT\text{-}rec}$ and $t_{3T\text{-}rec}$ are then plotted against I_p by symbols in Fig. 10, follow which dashed and solid lines are also drawn showing the correlations of $t_{LT\text{-}rec}$ and $t_{3T\text{-}rec}$ versus I_p determined based on the settlement measurement for clayey soils pre-subjected to cyclic loading history.

The time to EOP based on the pore water pressure measurement

In order to confirm the end of primary consolidation of specimen in the recompression stage after undrained cyclic shear, the dissipation of the cyclic shear-induced pore water pressure was typically measured for several tests and shown in Fig. 11 for different clayey soils. Similar to the tendencies in Fig. 7, by permitting the drainage, the pore water pressure inside the specimen dissipates until approaching zero and the time at this point, as symbolized by $t_{PT\text{-}rec}$, can be defined as the time to EOP determined by the pore water pressure measurement for the soils subjected to cyclic loading history.

The changes in $t_{PT\text{-}rec}$ with I_p are shown in Fig. 12 together with the obtained $t_{LT\text{-}rec}$ - I_p and $t_{3T\text{-}rec}$ - I_p relations for comparison purpose. Despite of several scattering on observed results of $t_{PT\text{-}rec}$, reasonable agreements between $t_{PT\text{-}rec}$ and $t_{3T\text{-}rec}$ are seen and therefore, the *3-t* method is valid for determining the time to EOP of clayey soils pre-subjected to cyclic loading history.

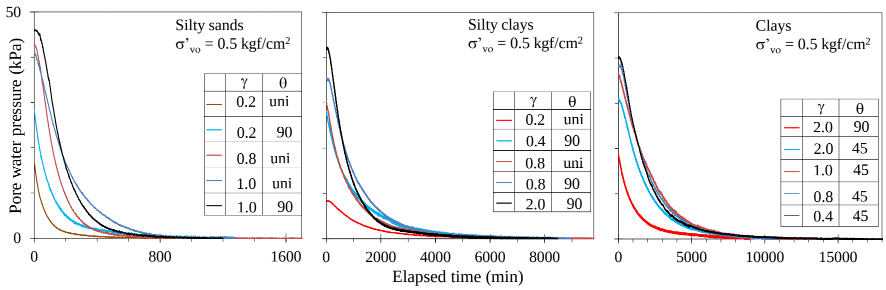


Fig. 11. Typical records of the pore water pressure dissipation in different clayey soils pre-subjected to cyclic loading

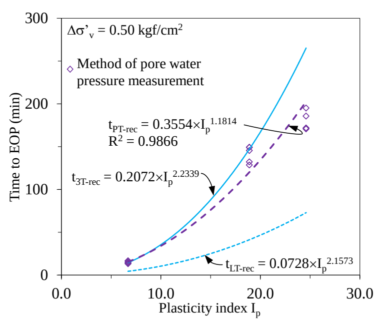


Fig. 12. Relations between the time to EOP determined by different methods and I_p for clayey soils pre-subjected to cyclic loading history

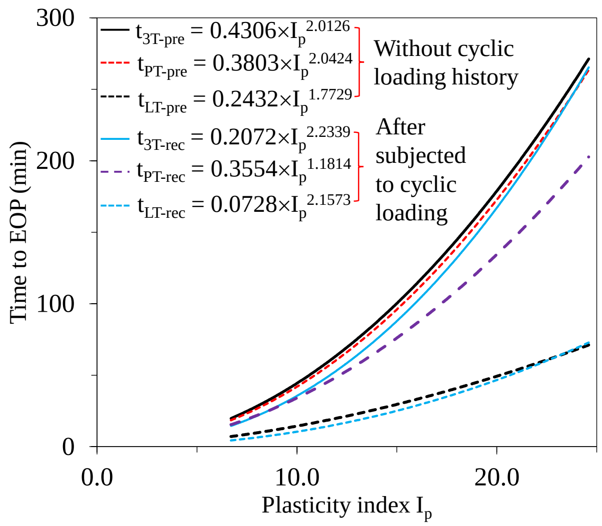


Fig. 13. Relations between the time to EOP determined by different methods for clayey soils with and without subjected to cyclic loading history

In Fig. 13, obtained relations between the time to EOP determined by different methods and the plasticity index are shown for both cases of specimen with and without subjected to cyclic loading history. The plots indicate that the time to EOP determined by *3-t* method agree well with those obtained from the measurement of the pore water pressure dissipation and therefore, *3-t* method should be used when the full pore water pressure dissipation in cohesive soils is needed for laboratory measurement. Also in Fig. 13, it is suggested that undrained cyclic shear slightly reduces the time required for the EOP of cohesive soils, at least for the range of plasticity index from I_p = 6.7 to 24.6. As confirmed by Yasuhara and Andersen [4], the soil would suffer structural disturbance when subjected to cyclic shear and since the bond between soil particles is decreased due to such a disturbance, the movement of the pore water becomes easier resulting in shorter duration for the dissipation of the pore water pressure.

4 Conclusions

The main conclusions obtained from the above experimental study on the time to EOP of soft clayey soils are as follows:

1. The time to EOP determined by *3-t* method reasonably agrees with those obtained by the measurement of the pore water pressure dissipation and being considerably larger than those determined by the Log Time method.

2. Since the pore water pressure dissipation is considered as a criterion for determination of the EOP, such above agreements suggest that *3-t* method should be introduced and applied in Vietnam as its wide application abroad.

3. The undrained uni-directional and multi-directional cyclic shears slightly affect the time to EOP of cohesive soils by which the time to EOP of specimen subjected to cyclic loading is slightly shorter than those of specimen without cyclic loading history.

4. The Atterberg's limit also affects the time to EOP of cohesive soils. The soils with higher Atterberg's limit show longer time to the EOP. By using the testing programs in this study, correlations between the time to EOP and the plasticity index can be obtained for both cases of clayey soils with and without subjected to cyclic loading history, at least for the range of plasticity index from I_p = 6.7 to 24.6.

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