Hardening process of clayey soils with high water content due to thixotropy effect

Processus de durcissement des sols argileux à forte teneur en eau causé par un effet thixotropique

Tanaka H.
Hokkaido University, Sapporo, Japan

Seng S.
Institute of Technology of Cambodia, Phnom Penh, Cambodia

ABSTRACT: Hardening due to thixotropy for clayey soils with high water content was studied by change in stiffness by time, using Bender Element Test. Shear strength was also measured to be compared with the increase of the stiffness measured by the bender element. Following interested findings are obtained: 1) the effect of thixotropy is found significantly at around the liquid limit state and less remarkable at the lower and higher ranges than the liquid limit; 2) the shear modulus at liquid limit after 24 hours resting is around 200 kPa; 3) the increment of the shear modulus developed in the thixotropy process appears noticeably higher than that in the secondary consolidation process. It is believed that these findings are very useful to establish a new theory for the consolidation of the ground filling by very soft clays or dredged soils with extremely high water content as well as to understand the effects of ageing on consolidation properties of natural soils.

RÉSUMÉ : Le durcissement de sols argileux, ayant une teneur en eau élevée et causé par la thixotropie, a été étudié à l'aide de plaques de piézo-céramiques permettant de suivre les changements de rigidité du sol en fonction du temps. La résistance au cisaillement a aussi été mesurée et comparée aux changements de rigidité. Ceci a permis les constatations intéressantes suivantes : 1) l'effet du gain thixotropique devient significatif lorsque l'état du sol est proche de la limite de liquidité lequel serait moindre aux valeurs supérieures et inférieures à la limite de liquidité; 2) le module de cisaillement à la limite de liquidité, après 24 heures au repos, est d'environ 200 kPa; 3) l'augmentation du module de cisaillement causée par la thixotropie apparat, d'une façon notable, plus élevée que celle pouvant provenir de la consolidation secondaire. Nous croyons que ces constatations sont très utiles pour établir une nouvelle théorie de la consolidation pour les cas de remblayage avec des argiles très molles ou des sols de dragage tout autant que pour comprendre les effets du vieillissement sur les propriétés de consolidation des sols naturels.

KEYWORDS: Thixotropy, Stiffness, Bender Element, Consolidation, Liquid limit.

1 INTRODUCTION

The concept of "effective stress" has been widely accepted by geotechnical engineers and it is believed that geotechnical parameters such as strength or stiffness can be simply correlated with the effective stress. In this concept, these parameters are independent of time and the apparent time dependency during consolidation can be understood by changing in the effective stresses in the process of the dissipation of the excess pore water pressure. On the other hand, some behaviors opposite to the effective stress approach are also recognized, i.e., thixotropic hardening. Soil loses strength or stiffness by remolding, but they are recovered in time. It may be considered that this factor should play an important role in the process of settlement. Thus, this paper will try to understand the thixotropic hardening phenomenon of clays with high water content.

Although some experimental data have been reported on this field, the conventional destructive testing tools such as triaxial, unconfined compression, and laboratory vane apparatus have been employed by previous investigators to measure strength hardening due to thixotropy. Normally, these methods do not guarantee the same testing condition because of using different samples and relatively long preparation time for testing, i.e., difficult to measure properties at very early time, and also disturbance effect occurs during insertion of the vane blade, for example. To overcome these drawbacks, a nondestructive bender element test, which provides the measurement at a very low strain level as small as 10^{-5} (0.001%), is introduced in this paper to study the thixotropic behavior of very soft clays, together with a vane shear test measuring the undrained strength. In another approach, oedometer test under very low pressure was also carried out, being equipped with the bender element to examine the development of soil stiffness due to consolidation. Correlation between the stiffness and the effective stress will be established, and also study on the changing in the stiffness during the secondary consolidation. Using these test results, the increment of stiffness caused by thixotropic behavior is tried to be evaluated.

2 SAMPLE AND TESTING METHOD

The tests were run on very soft clays using samples obtained from three commercial powder clays and three natural clays. Commercial clays are Fujinomori, Kasaoka, and NSF. The natural ones are Ariake, Hachirogata and Tokuyama. Their index properties are summarized in Table 1. Their liquid limits vary in a large range from low (48.6 %) to very high (246.0 %) value that allows this study to cover the wide different characteristic of materials.

After mixing at a target water content, the sample was poured into a mold with various sizes for different purposes: a plastic cylindrical mold with the height of 10 cm and the diameter of 5 cm for the bender element test, a gallon bucket with 20 cm of the diameter and heights of specimen varied from 7 to 8 cm for the vane test, and a consolidometer cell with diameter of 10 cm and adjustable height from 4 to 15 cm for consolidation test. Vibration was gently applied to drive out air bubbles from a slurry specimen and a sample was compacted when its water content was small and the sample was stiff. The mold with the specimen for the thixotropy test was wrapped by

Table 1. Geotechnical Properties used in the test.

Soil Types	Symbol in Figures	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index	Particle Density (g/cm^3)
Fujinomori	F	21.3	48.6	27.3	2.69
Kasaoka	K	27.5	62	33.5	2.61
NSF	N	29	55	26	2.76
Ariake	A	31.4	72.5	41.1	2.621
Hachirogata	H	96.5	246	149.5	2.43
Tokuyama	T	40	110.6	70.6	2.62

thin plastic film, and then it was kept in a high humidity box to prevent the water evaporation. The elapsed time for thixotropy was accounted just after the sample was poured into the mold.

As input signals for the bender element test, sine and rectangular waves have been alternatively used with wide ranges of frequencies in accordance with material stiffness, in order to attain a clear output waveform. Generally, the high frequency is required in testing stiff soils and vice versa. The "start-to-start" method for determining the arrival time (Δt) and "tip-to-tip" method for determining the travel distances (Δd) of the shear wave were adopted in this study (Yamashita et al., 2009).

The increase in the undrained shear strength during thixotropic hardening was also confirmed by the vane shear test. The vane diameter and height used in this experiment were 20 mm and 40 mm, respectively. The shear rate of the laboratory vane apparatus was constant at 6° rotations per minute. All tests were carried out for the same sample created by a gallon bucket, as already mentioned.

3 THIXOTROPIC EFFECT MEASUREMENT

3.1 *Shear Wave Velocity and Shear Modulus by Bender Element Test*

Figure 1 shows an example of increase in the shear wave velocity (V_s) with time, measured by the bender element test on a specimen made from Kasaoka clay mixed with 60.6% of water content. Since the water content of the specimen was almost equal to liquid limit state, the received shear wave signals at the beginning of the measurement were hardly identified because of their low amplitude and frequency. P-waves clearly appeared since they could propagate through liquid. As time was proceeded, the soil became stiffer; consequently the arrival times were detected more shortly, in another word the shear wave velocity increased. It may be considered that the increase in shear wave velocity (V_s) corresponds to the increases in the stiffness, which is reflected to the thixotropic phenomenon. The received shear waves became much clearer with high amplitude and frequency after a certain time, while P-waves seemed to decay.

The shear modulus (G) derived from V_s with elapsed time is illustrated in Fig. 2, where the symbols of A, F, K, N, H, and T represent Ariake, Fujinomori, Kasaoka, NSF, Hachirogata, and Tokuyama clays respectively with sample number. The number in the brackets indicates the water content (w) and the normalized water content by the liquid limit (w/w_L). It can be seen from the figures that G values for all conditions increases with time even at over limit liquid states. And, G builds up nearly in proportion to time in the logarithm scale, but this magnitude is certainly depended on types of soils and the amount of water content.

Since G increases in time, G at 24 hrs (G_{24}) will be a represented parameter for identifying characteristics of soil types and influence of water content. G_{24} is plotted in Fig. 3

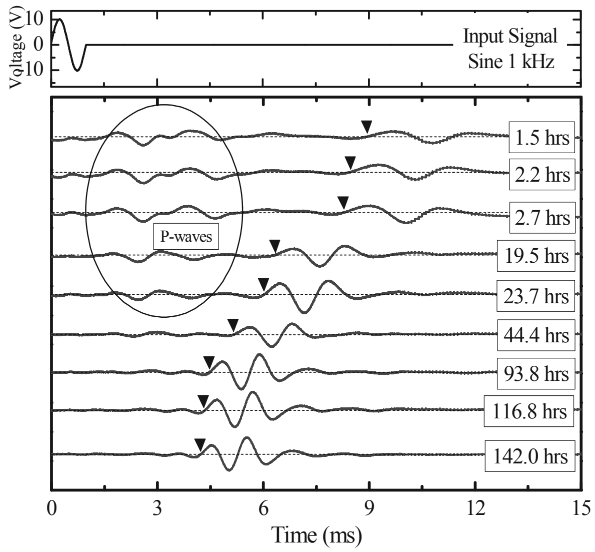

Figure 1. An example of shear waves (Kasaoka clay, w=60.6%)

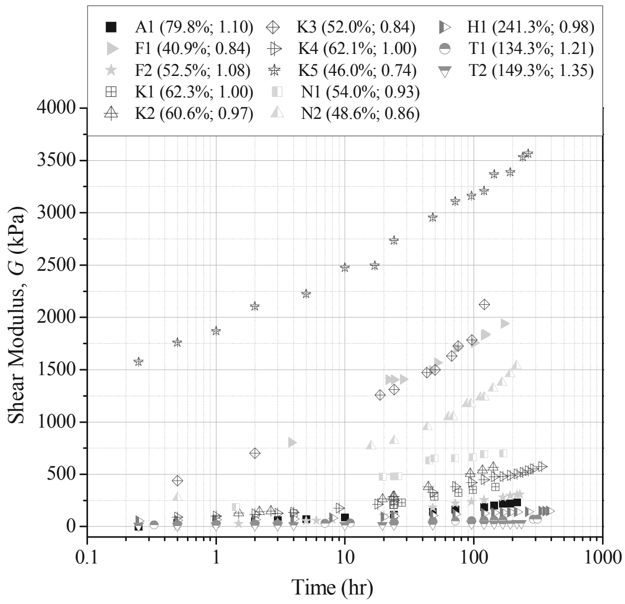

Figure 2. Relationships between G and time.

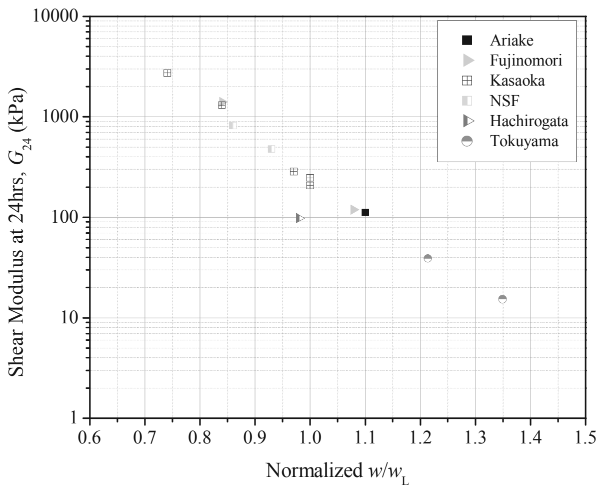

Figure 3. Relationship between w/w_L and G after 24 hours.

against the (w/w_L), considering different types of materials. A clear correlation between these two parameters can be observed with minor scatters. Obviously, G decreases with increasing the normalized w/w_L, meaning that w_L defines the magnitude of G regardless types of soils. In this case, G_{24} value at w_L appears around 200 kPa.

By extruding data of Hachirogata clay, because of a strange point in the G_{24} and w/w_L relation as shown in Fig. 3, the correlations of hardening G and normalized w/w_L at not only 24 hours but also various times are plotted in Fig. 4 to examine the effect of thixotropy corresponding to wide range of water content. It can be seen in the figure that the increment of G to time at around w_L is the largest, while at smaller water contents than w_L, say, when w/w_L is less than 0.8, the tendency of G increasing against time becomes smaller.

3.2 *Undrained Shear Strength by Vane Test*

Although the figure is not presented in this paper, it is also observed in laboratory vane test that the shear strength increases with time. The values of s_u measured at 24 hrs (s_{u24}) are plotted with normalized w/w_L in Fig. 5, in the same manner as G_{24} shown in Fig. 3. Almost a linear correlation between s_{u24} in the logarithm scale and w/w_L ratio is also identified, but more remarkable scatters and slightly steeper gradient are recognized than those in Fig. 3. At w_L, the magnitude of s_{u24} varies from about 1 to 2 kPa, whose values are somewhat lower than those suggested by Wood (1990), who did not consider the thixotropic hardening effect and recommended 2 kPa of s_u at w_L.

Relationship between thixotropic hardening G and s_u at various elapsed times is shown in Fig. 6 together with that obtained from cement-treated soil (CTS) material proposed by Seng and Tanaka (2011). They found that G and s_u relation of CTS can also be applicable to most of worldwide natural clays with s_u varied from 10 to 150 kPa. It is observed in Fig. 6 that at very high water content corresponding to low initial strength, s_u remains constant until a certain time unlike G. After G reaches a certain values, s_u starts to increase and the relation of G and s_u seems to approach to the same line as CTS. Indeed, Seng and Tanaka (2011) reported that even CTS material behaves the similar way when the strength of CTS is extremely small. However, when strength of CTS is greater than 1 kPa, the G and s_u correlation for each sample forms linear function, unlikely very soft clays that show a monotonic increase. Both behaviors, the constant values and slow increases of s_u, are quite interesting and might be associated with viscosity or strain rate effect which is obviously an important factor governing soil strengths especially when material remains soft; however further investigation is necessitated to confirm this presumption.

4 SHEAR MODULUS MEASUREMENT DRUING SECONDARY CONSOLIDATION

The development of G during secondary consolidation is also an interesting topic. It should be noted that the condition of the secondary consolidation is under a constant effective stress but the volume is changing, while in the thixotropic condition, the volume change does not take place. Therefore, it may be anticipated that the increase rate of hardening G owing to the secondary consolidation should be greater than that of thixotropy, as decreasing void ratio during the secondary consolidation. As shown in Figs. 7 and 8, however, the increase in G during the secondary consolidation is considerably smaller than that in Thixptropy test. Figure 7 shows test results from the thixotropy test, where G is normalized by G at 1 hour after remolding (G_{at1h}). In Fig. 8, change in G during the secondary consolidation is shown. The end of primary consolidation (EOP) was estimated by the root t method, and it is assumed that the effective stress is constant after EOP. Both axes in the figure are normalized by time at EOP (t_{EOP}) and G at EOP

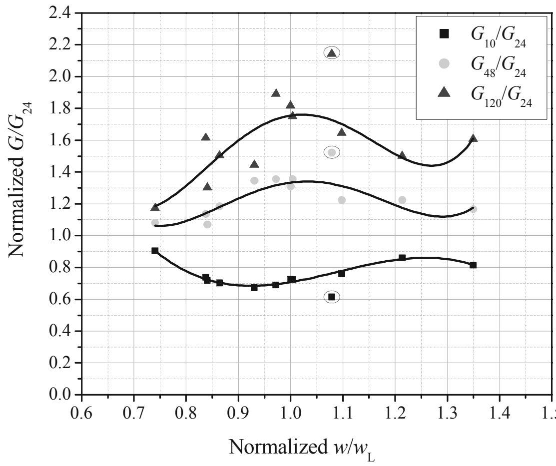

Figure 4. Increase in G due to time at different w.

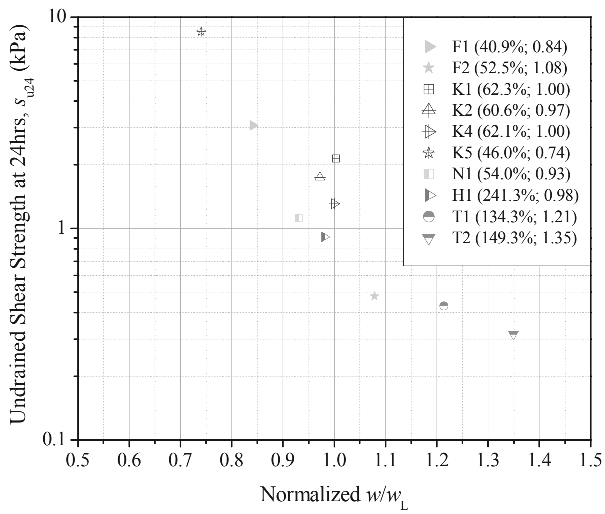

Figure 5. Relationship between w/w_L and s_u measured by vane after 24 hours.

(G_{EOP}). The reason for small increment G during the secondary consolidation might be explained by destruction of the interparticle bounding, which is created during the thixotropy process.

5 CONCLUSIONS

The experimental results of thixotropic phenomenon measured on various clays are presented and compared with values obtained by consolidation test with low pressures. Main conclusions can be drawn as following:

1) Bender element test is a powerful tool and an appropriate method for evaluating the thixotropic hardening stiffness of very soft clays, since it are able to detect even small changes in G with an extremely small strain.
2) G at 24 hours for w_L is around 200 kPa.
3) Regardless of soil types, thixotropy affects the clay most strongly at around liquid limit state and becomes less remarkable at lower and higher water contents.
4) The correlation between G and s_u for very soft clays is analogous to that of cement-treated soil proposed by Seng and Tanaka (2011). Additionally, similar behavior is recognized at very low strengths, where s_u appears constant while G increases.

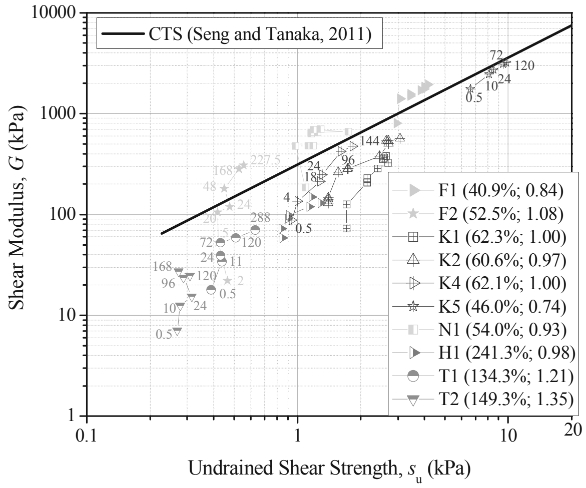

Figure 6. Relation between G and s_u. Numbers in the figure indicate the elapsed time after remolding.

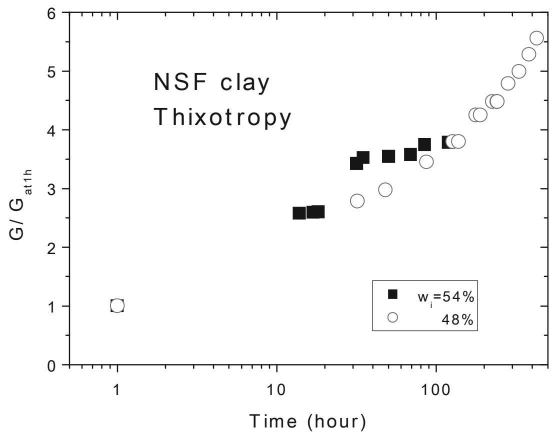

Figure 7. Increase in *G* during thixotropy test.

5) The increment of the shear modulus under secondary consolidation is shown relatively low, compared with that developed during the thixotropic process. It is suggested that these differences may caused by the different constraint pressures between the secondary consolidation and thixotropic condition, i.e., the free arrangement of soil particles is prevented under the former condition, while under thixotropic condition, the soil particles can be freely arranged.

From the present study, we can point out the importance of thixotropic hardening phenomenon for understanding soil behavior with high water contents. It is well known that the void ratio or water content in situ is much larger than that predicted by laboratory consolidation tests based on *e*-log*p*' relation at the EOP (for example, Tanaka et al., 2004). If we consider the secondary consolidation effect, in situ void ratio should be smaller than that predicted from *e*-log*p*' relation at the EOP. To cope with such inconsistency, Burland (1990) has proposed a concept of Sedimentation Consolidation Line (SCL), considering the cementation or fabric effect. Study on the thixotropy, which was conducted in the present study, is also expected to provide an important key to understanding such a phenomenon.

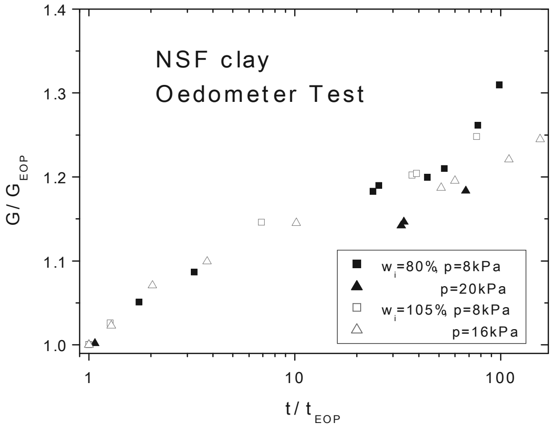

Figure 8. Increase in G during the secondary consolidaiton.

6 REFERENCES

Burland, J. B. 1990. On the compressibility and shear strength of natural clays, *Géotechnique* 40(3), 329-378.

Seng, S. and Tanaka, H. 2011. Properties of cement-treated soils during the initial curing stages, *Soils and Foundations* 51(5), 775-784.

Tanaka, H., Kang, M. S. and Watabe, Y. 2004. Ageing effects on consolidation properties –Based on the site investigation of Osaka Pleistocene clays- , *Soils and Foundations* 44(6), 39-51.

Wood, D. M. 1990. *Soil behavior and critical state soil mechanics*, Press Syndicate of the University of Cambridge, USA.

Yamashita, S., Kawaguchi, T. Nakata, Y., Mikami, T., Fujiwara, T. and Shibuya, S. 2009. Interpretation of international parallel test on the measurement of G_{max} using bender element, *Soils and Foundations* 49(4), 631-650.