Anisotropic strength ratio and plasticity index of natural clays

Étude de la relation entre l'anisotropie et l'indice de plasticité des argiles naturelles

Won J.Y.
Technip

ABSTRACT: A number of K_o-consolidated triaxial compression and extension test results were collected to re-evaluate the relationship between anisotropic strength ratio and plasticity index of natural clays. The database covers 203 pairs of triaxial tests performed on normally consolidated natural clays from 14 countries, published between 1972 and 2007. Data selection criteria were established for a consistent comparison. The anisotropy was strongly influenced by the definitions of failure in extension tests. Once the anisotropy data are grouped into their depositional environments, no general trend of anisotropy with plasticity index can be observed. The well-known trend that anisotropy decreases with plasticity index cannot be justified. A trend of anisotropy correlated exclusively with plasticity index can be misleading. Anisotropic characteristics of a natural clay should be evaluated by careful consideration of site specific characteristics, spatial variability, depositional and post-depositional environments of the clays.

RÉSUMÉ : Des résultats d'essais triaxiaux K_o-consolidés en compression et en extension ont été collectés pour réexaminer la relation entre l'anisotropie et l'indice de plasticité des argiles naturelles. Les données consistent en 203 séries d'essais sur des argiles normalement consolidées de 14 pays, et publiés entre 1972 et 2007. Un critère de sélection des données a été établi pour faire des comparaisons cohérentes. L'anisotropie est fortement corrélée avec le type de rupture en extension. En groupant les données en fonction de leurs conditions de dépôts, aucune corrélation entre l'anisotropie et l'indice de plasticité n'est observée. La diminution bien connue de l'anisotropie en fonction de l'indice de plasticité reste inexpliquée. Considérer que l'anisotropie ne dépend que de l'indice de plasticité serait erroné. L'anisotropie d'une argile naturelle doit être évaluée en tenant compte soigneusement des caractéristiques spécifiques du site, de la variabilité spatiale, des environnements de dépôts et post-dépôts de l'agiles.

KEYWORDS: Clay, Undrained Shear Strength, Anisotropy, Plasticity, Triaxial Test, Extension Test.

1 INTRODUCTION

Undrained shear strength of natural clays shows anisotropy, i.e. it displays different undrained shear strengths under different shear stress conditions and directions. Anisotropy in stiffness, permeability, and shear strength comes from stress-induced and inherent anisotropy. Anisotropic characteristics of natural clays play a significant role in many geotechnical applications, such as slope stability, and bearing capacity of shallow and deep foundations both in onshore and offshore applications. Anisotropy is routinely investigated for offshore foundations (driven piles and suction anchors). In onshore projects, however, the anisotropy is seldom investigated because of many reasons. In many cases, thus, geotechnical engineers resort to empirical trends to evaluate anisotropy of the soil of interest.

It is generally known that the anisotropy decreases with plasticity index, i.e. high plastic clays are more isotropic than low plastic clays. The trend was reported by Berre and Bjerrum (1973) and Ladd et al. (1977) decades ago, based on a limited number of test results. Besides the debates whether or not plasticity index alone can represent soil characteristics, there have been numerous anisotropy test results published since then. Therefore, it is worthwhile to collect and analyze the available anisotropy information to re-evaluate the anisotropic undrained shear strength characteristics of natural clays.

A number of published K_o-consolidated triaxial compression and extension tests performed on normally consolidated natural clays were collected. A total of 203 pairs of K_o-consolidated triaxial compression and extension test results from 14 countries were analyzed. Different test conditions and methods of the data necessitated consistent data selection criteria. The data were grouped into their regions and/or depositional environments. This paper presents review on depositional environments, discussion on test conditions, and re-evaluation of the generally accepted anisotropy trend.

2 METHODOLOGY

From an extensive literature review, K_o-consolidated anisotropy test results were collected. The published data and test conditions were carefully reviewed to select acceptable data. The database was, subsequently broken down into respective regions or depositional environments including Scandinavia, Canada, Europe, Middle East, Japan, and East Asia.

2.1 *Anisotropy*

In this study, the anisotropy was evaluated by K_o-consolidated triaxial compression (CK_oUC) and extension (CK_oUE) tests. Anisotropic strength ratio ($K_s=S_{uE}/S_{uC}$) was defined as the undrained shear strength ratio of extension strength (S_{uE}) to compression strength (S_{uC}). The higher the anisotropic strength ratio is, the lower the anisotropy is.

2.2 *Data selection criteria*

Anisotropy can be evaluated by various test methods such as plane strain, hollow cylinder apparatus, triaxial compression and extension tests as well as field vane tests with different shape and length of blades. Each method measures different aspects of anisotropy. Only CK_oUC and CK_oUE test results on undisturbed natural clays were selected and analyzed. For consistency, data from other test methods were excluded. It was found that many published data did not include detailed test conditions. To avoid unnecessary discussion on the effects of consolidation methods for anisotropic triaxial tests, only the results that followed the recompression concept i.e., consolidate the specimen to an estimated in-situ overburden stress (σ'_{vc}) before the undrained shear, were selected. Many test data for USA clays were excluded because the majority of them were obtained from the SHANSEP (Stress History and Normalized Soil Engineering Parameters) approach. The following data selection criteria were established for a consistent comparison.

- Geologically normally consolidated clays
- Apparently (lightly) overconsolidated clays
- K_o (or anisotropically)-consolidated undrained triaxial
- Undisturbed natural clays
- Consolidation method: Recompression

- Inorganic clays

The data from the following conditions were excluded.

- Geologically overconsolidated clays
- Rotating angles of tested specimens
- Consolidation method: SHANSEP
- Isotropically consolidated triaxial
- Hollow Cylinder Apparatus test results
- Unconfined compression or unconsolidated undrained
- Organic clays and peat
- Artificial, remolded or resedimented clays

2.3 *Anisotropy database*

A total of 203 pairs of CK_oUC and CK_oUE test results were collected. The 53 resources reported by Mayne (1983) were also carefully reviewed following the data selection criteria listed above. The database covers 14 countries and data published between 1972 and 2007. A relatively large amount of anisotropy data (86) have been published for Japanese natural clays. Statistical information of the database is summarized in Table 1.

Table 1. Statistical information of the database

Area	Country	Local name	No. data	Plasticity Index	K_s (S_{uE} / S_{uC})
Northern	Finland	Kimola	1	31	0.70
Europe	Norway	Various sites	19	4~32	0.23~0.78
	Sweden	Various sites	4	26~53	0.63~0.79
Europe	Italy	Porto Tolle, Trieste	2	30~47	0.61~0.81
	France	Various sites	3	54-67	0.49~0.64
	UK	Bothkennar	9	28~43	0.36~0.58
North	Canada	NBR and other sites	21	5~57	0.41~0.74
America	USA	Gulf of Mexico	2	33~55	0.78~0.79
Asia	Iraq	Khor Al-Zubair, Fao	10	18~36	0.50~0.89
	Japan	Osaka bay	25	50~71	0.55~0.91
		Izumo	21	25~104	0.69~1.06
		Ariake	13	36~81	0.60~1.00
		Kinkai	11	22~80	0.64~1.08
		Tokyo bay	8	36~50	0.59~0.73
		Various sites	8	35~75	0.48~0.64
	Indonesia	Banjarmasin, Surabaya	3	60~85	0.65~0.83
	Singapore	Singapore	3	34~58	0.88~1.08
	Thailand	Bangkok	12	26~77	0.74~1.27
	Korea	Namak	20	22~41	0.45~0.65
		Shihwa	8	14~25	0.66~0.89
	14 countries		203	4~104	0.23~1.27

2.4 *Definitions of failure in extension test*

There are two common definitions of the failure for triaxial extension test (Tanaka et al. 2001a).

- Definition-A: strength at the same strain level (typically less than 2 %) as the peak strength from a compression test
- Definition-B: peak strength (necking failure) or strength at 15 % of axial strain if the peak is not observed

It is evident that undrained shear strength values from CK_oUE will be significantly different, depending on the definitions of failure. An example of the different failure definitions is shown in Figure 1: A specimen from 8.4m depth has S_{uC}/σ'_{vc}=0.202 and the corresponding extension specimen has S_{uE}/σ'_{vc}=-0.118 and -0.164 following the failure definition-A and -B, respectively. The difference in anisotropic strength ratio between the definition-A (K_s=0.584) and B (K_s=0.812) is about 40 %. Irrespective of the failure modes (necking or ductile) in extension tests, the difference between the two failure definitions will be substantial. Many published data did not have its definitions of failure for either triaxial compression or extension tests.

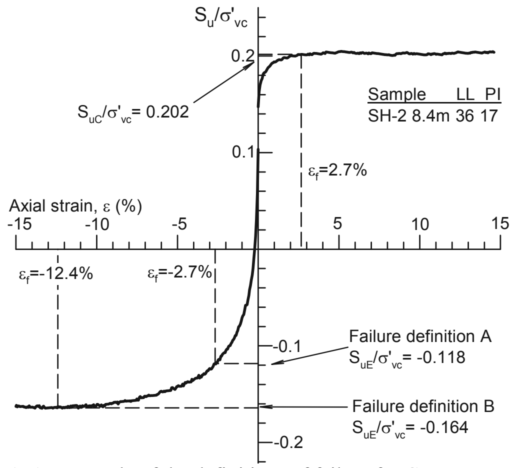

Figure 1. An example of the definitions of failure for CKoUE test.

2.5 *Strain rate effects*

It was found that many authors and institutes used different strain rates for the undrained shearing. For example, strain rates of the undrained (compression/extension) shearing were 0.75 %/hr for NGI in Norway, 6.0 %/hr for PHRI in Japan, 0.18 %/hr for UK, 0.5 %/hr for USA. The two Korean marine clays were sheared at 3.0 %/hr. Strain rate effects on anisotropy are not covered in this study and are assumed to be insignificant.

3 DEPOSITIONAL ENVIRONMENTS

For further comparison, it is vital to review depositional and post-depositional environments of the clays presented in this study, with regard to their physical and geotechnical properties.

3.1 *Scandinavian clays*

Depositional environments and the following geological events (leaching) in Scandinavian clays were well documented by Bjerrum (1954) as the causes of quick clay formation. A typical feature of glacially derived clays is that the clay fraction (< 2 μm) contains considerable quantities of non-clay minerals (rock flour). For example, the rock flour of the Drammen clay was produced by the abrasive action of glacial ice during the Ice Age (Tanaka et al. 2001a). As a result, the Drammen clay has a high clay-size fraction (40-50%) but plasticity index is approximately 20 (Tanaka and Tanaka 1997).

3.2 *European and Gulf of Mexico (USA) clays*

Unlike the well-documented Bothkennar clay in the United Kingdom (Nash et al. 1992, Tanaka et al. 2003), depositional environments of the other European clays are not readily available. The Bothkennar clay is characterized as a Holocene deposit with low clay fractions. Abundant thin laminations and mottled features are commonly observed. Overconsolidation ratios are about 2 without any stress changes after its deposition, is most probably caused by ageing or cementation. The Bothkennar clay was formed since 8,500-6,000 years B.P. (before present) under an estuary environment. The Italian and French clays in the database are geologically normally consolidated deltaic clays. Information of the depositional environments of the two data points from an offshore site, Gulf of Mexico, USA is not available. However, the marine clay deposits in the Gulf of Mexico are known as geologically normally consolidated Pleistocene or Holocene clays, except for the cases where excess pore pressure is present. Abundant smectite, yet moderate sensitivity (2~4) are the known characteristics.

3.3 *Canadian clays*

Depositional environments of the Canadian cemented clays were described by Lefebvre et al. (1983), Tanaka et al. (2001b), and Tanaka et al. (2003). Typical Canadian clays are of marine origin, cemented and were lifted to the present elevation due to the isostatic movement after the end of the Ice Age. Overconsolidation ratios over 2 are believed to be a result of cementation. Mineralogy of the Canadian quick clays can be summarized as high amorphous minerals and abundant clay-size rock flour (non-clay minerals).

3.4 *Japanese clays*

Most Japanese marine clays are characterized as non-glacial, pyroclastic and low-swelling smectitic clays with clay fractions of about 50%. A well-developed flocculated structure combined with abundant fossil remains was mostly derived from diatoms (Ohtsubo et al. 2000, Tanaka et al. 2001b, Tanaka et al. 2003). Most of the Japanese marine clays have been developed since 8,000 years B.P., when the rapid sea-level rise commenced in the late Quaternary era (Hanzawa and Tanaka 1992).

3.5 *Asian clays*

The Bangkok clay is a non-glacial, high-swelling smectite, non-pyroclastic origin clay (Ohtsubo et al. 2000). Microfossils, such as diatom or foraminifera are rare (Tanaka et al. 2001a). Clay fractions of the Bangkok clay are typically over 50 %. The Iraqi clays and the Korean marine clays in the database are with non-swelling minerals, non-glacial origin, and non-pyroclastic. Sedimentation time of Iraqi clays is about 5,000 years B.P. (Hanzawa and Tanaka 1992). Depositional and post-depositional environments of the Korean marine clays were described in details by Won and Chang (2007). The Shihwa clay is silt-dominant, whereas the Namak clay is clay-dominant.

4 DISCUSSION

Decades ago, Berre and Bjerrum (1973) and Ladd et al. (1977) reported that anisotropy of clays decreases as plasticity index (PI) increases. In other words, the anisotropic strength ratio (K_s=S_{uE}/S_{uC}) increases with PI. This trend was followed by many researchers (for example, Mayne, 1983, Jamiolkowski et al. 1985). Until Mayne (1983) compiled 66 anisotropic data points, the trend was supported only by 16 data points including 4 plane strain data and 12 triaxial data on undisturbed or resedimented samples, mainly from Scandinavian clays and a mixture of recompression and SHANSEP approaches. In the meantime, 53 resources compiled by Mayne (1983) included test results from different conditions and test methods, such as quick sand, remolded specimens, overconsolidated soils, and unconfined compression tests on different trimming angles.

In this study, anisotropic data following the data selection criteria are grouped into their regions and depositional environments (Figure 2). If all the data are plotted in one space, the trend can be biased by the dominant number of test sets, for example Japanese clays. Furthermore, one can treat different clays with the same PI as the similar clays, even though they have different mineralogy, clay structures, and clay fractions, i.e. different deposition environments. Anisotropic strength ratios of the Scandinavian clays in Figure 2(a) show a wide spread within a small range of PI. Anisotropy data for the Scandinavian clays reported by Berre (1982) and Berre and Bjerrum (1973) were based on failure definition-A. Since the Drammen clay typically shows strain hardening behavior and does not have peak extension strengths (Berre and Bjerrum 1973, Ladd et al. 1977, Hanzawa and Tanaka 1992), the extension strengths by definition-A resulted in much less K_s than ones by definition-B. In fact, Ladd et al. (1977) and Berre (1982) have mentioned that extension strengths determined by the definition-A can be somewhat too low; hence the K_s values for the Norwegian low PI clays reported by Berre (1982) and Berre and Bjerrum (1973) must have been underestimated. Moreover, Tanaka and Tanaka (1997) have reported anisotropy data for the Drammen clay (filled circles in Figure 2(a)), which were quite different from the results by Berre and Bjerrum (1973). Tanaka and Tanaka (1997) reported K_s ranging 0.32-0.78 for PI=15-32, whereas the range of K_s was 0.265-0.4 by Berre and Bjerrum (1973) for the same lean and plastic Drammen clays. Tanaka and Tanaka (1997) must have followed the failure definition-B. If the anisotropy data for Scandinavian clays were based on the failure definition-B at the beginning, the anisotropy trend with PI would have been quite different.

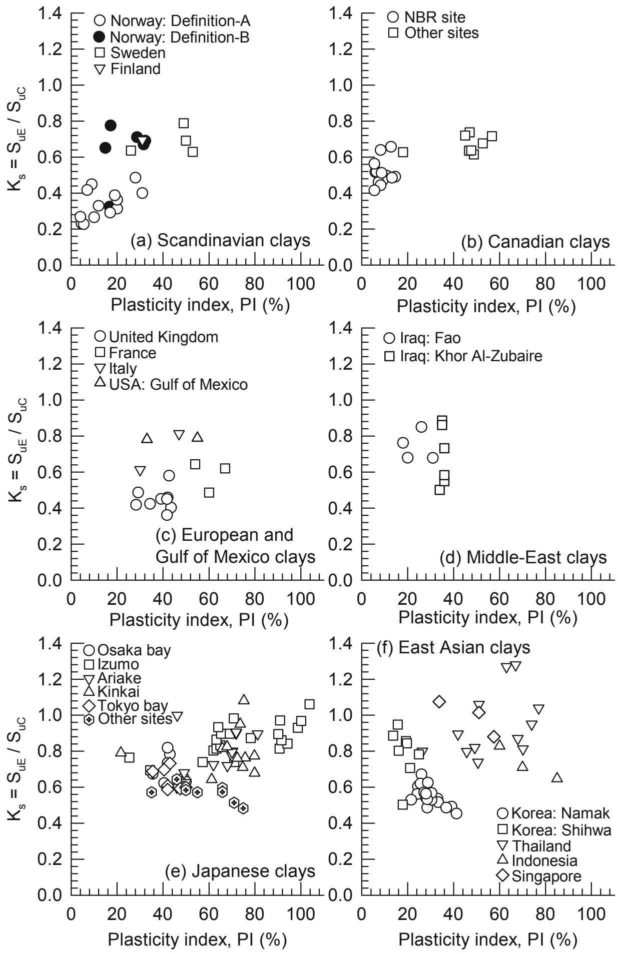

Figure 2. Anisotropic strength ratio versus plasticity index for different depositional environments.

For Canadian clays in Figure 2(b), the published data can be grouped into (1) low PI, sensitive and highly structured clays, and (2) structured clays with high PI. The majority of the low PI group are of the NBR site (Lefebvre et al. 1983), where an intensive test program has been performed on the marine clay with PI=5-15. Among the anisotropy data from the NBR site, only the data that satisfied the data selection criteria are presented. The failure definition-B (necking failure) was used for the NBR site. The K_s values in the NBR site varied between 0.41-0.66, depending significantly on the degrees of structure, within a narrow PI range. The majority of the high PI group data are from the Champlain Sea area. The difference between the low and the high PI groups seems to be originated from mineralogy of the clay size particles; the low PI clays consist of rock flour for clay-size particles, whereas the high PI clays consist of illite, chlorite, and vermiculite (Tanaka et al. 2001b). Distinctively different characteristics of the two groups make it difficult to draw a trend line for the Canadian clays.

Anisotropic data from Gulf of Mexico and the data of European clays are plotted together in Figure 2(c) because their depositional environments seem to be similar. Anisotropic strength ratios from the Bothkennar site ranged between 0.36 and 0.58 with PI range of 28-43. Peak or necking failures were observed (definition-B) from the samples retrieved by Laval and Sherbrooke samplers. No apparent trends between K_s and PI can be observed in Figure 2(c).

The only anisotropy data from the Middle East are of Iraqi clays as shown in Figure 2(d). The Iraqi clays in the database are normally consolidated young or aged clays. The anisotropy substantially changes (K_s=0.50-0.89) within a very narrow PI range (PI=34-36) for the Khor Al-Zubaire clay.

Anisotropic data of Japanese clays are presented in Figure 2(e). It is clear both K_s and PI values significantly vary even within a specific site. For example, the Izumo clay has PI range of 25-100 and K_s values of 0.70-1.06. From Figure 2(e), one could suggest K_s=0.5-0.8 for PI=20-60 and K_s=0.7 or more for PI over 60, for Japanese clays. Spatial variation within a site as well as locality seems to have strong effects on anisotropy than a single index property, PI.

Anisotropy data from the East Asian countries are shown in Figure 2(f). All the anisotropy data followed the failure definition-B. Anisotropic strength ratios typically ranged between 0.5 and 1.1 for the wide PI range of 14-85. The Namak clay is similar to the Bothkennar clay in many ways including stress history, organic contents, laminated features, and estuary environments. The K_s range of the Namak clay is 0.45-0.67 with PI=22-41 that is comparable to the Bothkennar clay. Of special interest is anisotropy data from the Bangkok clay. Berre and Bjerrum (1973) presented only one data point that was not from the Scandinavian Peninsula and PI over 35: from Bangkok east. In fact, the data point (K_s=0.52 & PI=88) was not selected in this study because it appeared to be an organic clay. As for Bangkok clay, published data show a wide range of K_s=0.74-1.28 with PI=26-77. As Tanaka et al. (2001a) mentioned, Southeast Asian clays seem to behave more isotropically despite the scatter and their moderate PI values.

When Berre and Bjerrum (1973) and Ladd et al. (1977) reached the conclusion that anisotropy of clays decreases with plasticity index, very limited test results were available. Scandinavian low PI clays with failure definition-A that underestimated S_{uE} formed the left lower end and the two data points from Bangkok organic clay and Atchafalaya clay, USA (PI=75 and definition-B) formed the right end to conclude the trend. Once the anisotropy data with consistent criteria in this study are grouped into their depositional environments, the trend of K_s increase with PI can hardly be observed. The statement "less plastic, and often more sensitive, clays tend to have higher anisotropy than more plastic clays" by Jamiolkowski et al. (1985) appears to be appropriate, only if the less plastic and sensitive clays are Scandinavian and Canadian low PI clays. This study supports the conclusion by Hanzawa and Tanaka (1992) that undrained strength anisotropy is not correlated with plasticity index. Other aspects, such as clay fraction, clay structure, mineralogy, origin, diatoms, spatial variation are the major factors that control anisotropy in shear strength of natural clays. In other terms, depositional and post-depositional environments, and regional variations are the governing factors for anisotropy of natural clays, rather than a single index property like PI. It should be emphasized that index properties are good indicators of those major governing factors in a limited sense. For a given local soil, a carefully selected empirical correlation or a trend based on local data should be valid and useful. However, a comparison between various natural clays solely by a single index property such as plasticity index, without careful consideration of depositional and post-depositional environments can be misleading.

5 CONCLUSIONS

A large number of anisotropic triaxial test results (CK_oUC and CK_oUE) were collected and analyzed to re-evaluate the generally accepted trend between anisotropy and plasticity index. Data selection criteria were established for a consistent comparison. K_o-consolidated (recompression) triaxial test results on geologically normally consolidated, undisturbed natural clays were selected. Based on the analysis, the well-known trend that anisotropy decreases with plasticity index cannot be justified. The trend was developed by limited test results and different definitions of failure. Anisotropy was strongly influenced by the definitions of failure in CK_oUE tests. When comparing different natural clays, an anisotropy trend correlated exclusively with plasticity index can be misleading. Clay structure, clay fraction, mineralogy, origin, diatoms, and spatial variation are the governing factors for understanding anisotropy of natural clays. Relationship between anisotropic strength ratio and plasticity index should be evaluated by careful consideration of spatial variability, site characteristics, and depositional and post-depositional environments of an individual clay of interest.

6 REFERENCES

Berre T. 1982. Triaxial testing at the Norwegian Geotechnical Institute. *Geotechnical Testing Journal* 5 (1/2), 3-17.

Berre T. and Bjerrum L. 1973. Shear strength of normally consolidated clays. *Proc. 8th ICSMFE*, Moscow 1, 39-49.

Bjerrum L. 1954. Geotechnical properties of Norwegian marine clays. *Geotechnique* 4 (2), 49-69.

Hanzawa H. and Tanaka H. 1992. Normalized undrained strength of clay in the normally consolidated state and in the field. *Soils and Foundations* 32 (1), 132-148.

Jamiolkowski M., Ladd C.C., Germaine J.T. and Lancellotta R. 1985. New developments in field and laboratory testing of soils. *Proc. 11th ICSMGE*, San Francisco 1, 57-153.

Ladd C.C., Foott R., Ishihara K., Schlosser F. and Poulos H.G. 1977. Stress deformation and strength characteristics. *Proc. 9th ICSMFE*, Tokyo 2, 421-494.

Lefebvre G., Ladd C.C., Mesri G. and Tavenas F. 1983. *Report of the Testing Subcommittee*. Committee of specialists on the sensitive clays on the NBR complex, SEBJ, Montreal, Canada, Annexe I.

Mayne P.W. 1983. Discussion: Undrained shear strength anisotropy of normally consolidated cohesive soils. *Soils and Foundations* 23 (4), 143-146.

Nash, D.F.T., Powell, J.J.M. and Lloyd, I.M. 1992. Initial investigations of the soft clay test site at Bothkennar, *Geotechnique* 42 (2), 163-181.

Ohtsubo M., Egashira K., Koumoto T. and Bergado D.T. 2000. Mineralogy and chemistry, and their correlation with the geotechnical index properties of Bangkok clay: comparison with Ariake clay. *Soils and Foundations* 40 (1), 11-21.

Tanaka H., Locat J., Shibuya S., Soon T.T. and Shiwakoti D.R. 2001a. Characterization of Singapore, Bangkok, and Ariake clays. *Canadian Geotechnical Journal* 38 (2), 378-400.

Tanaka H., Shiwakoti D.R., Mishima O., Watabe Y. and Tanaka M. 2001b. Comparison of mechanical behavior of two overconsolidated clays: Yamashita and Louiseville clays. *Soils and Foundations* 41 (4), 73-87.

Tanaka H., Shiwakoti D.R. and Tanaka M. 2003. Applicability of SHANSEP method to six different natural clays, using triaxial and direct shear tests. *Soils and Foundations* 43 (3), 43-55.

Tanaka H. and Tanaka M. 1997. Application of the UC test to two European clays. *Proc. 14th ICSMFE*, Hamburg 1, 209-212.

Won J.Y. and Chang P.W. 2007. The causes of apparent overconsolidation in the Namak marine deposit, Korea. *Geotechnique* 57 (4), 355-369.