

EXAMINATION OF PUSAN CLAYS AT A REFERENCE TESTING SITE

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ABSTRACT: In early 2000, five special testing sites were proposed by Dong-A University's Brain Korea 21 Project, to look into some unusual geotechnical characteristics of Pusan clays. In this paper, the concept of a reference testing site and the way in which it has been set up and investigated are presented. Some of the results of both laboratory and in situ testing at a reference site are reported for illustration. The newly obtained data were analyzed and presented using both conventional and novel approaches in soft clay engineering. The initial results have demonstrated the benefits of having a reference testing site for moving toward a better characterization of Pusan clays. Such a practice can be considered as a useful step in geotechnical investigation of low land areas in the Nakdong river plain.

INTRODUCTION

Due to large reclamation projects, a larger number of geotechnical investigations have been done in lowland areas in the Nakdong deltaic plain. Despite a long period of investigation over the past decade, Pusan clays have not been well characterized, especially in the coastal and estuarine areas. Some of the particular geotechnical problems facing Pusan clay characterization are worth mentioning:

(1) Sampling has been typically done only at some depth levels, mainly due to cost factors. Consequently, a complete characterization of the whole soil profile is usually lacking.

(2) The overconsolidation ratio, OCR, determined from traditional oedometer tests, are less than 1.0 for most depth levels, especially from 15 m or so downward.

(3) Although the field tests are commonly planned in a site investigation project, the data of SPT, field vane and piezocone have been little exploited, and consequently their value in soil investigation has been underestimated.

Facing this situation, and a rapid increasing demand for on-site investigation for large-scale reclamation projects in Pusan and its vicinity, the Brain Korea 21 Project (BK21), Dong-A University, has decided to set up some standard testing sites to help get a better characterization of Pusan clays. The aims of this paper are as follows: (i) to present the concept of a reference testing site for Pusan clays and the way it was set up and investigated; (ii) to present some geotechnical characteristics of Pusan clays which have been recently obtained at a reference testing site at Jangyu; and (iii) to provide some answers regarding particular geotechnical properties of Pusan clays which have stirred discussion among concerned researchers so.

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CONCEPT OF A REFERENCE TESTING SITE

For lowland development, a geotechnical investigation is usually expensive. Consequently, developers have always desired to have investigation results of good quality at a minimum expenditure. The quality of a geotechnical investigation depends on the following: code of practice; quality of drilling and sampling; testing equipment and procedure; knowledge of geology of the soil to be investigated and experiences from previous geotechnical investigations; expertise of field crew and of technicians in the laboratory.

It has often happened that different companies from one investigation to another have evaluated differently the geotechnical properties of the same soil. The situation is particularly true for investigation of Pusan clays over the past decade, as mentioned earlier. To better assess Pusan clays, in addition to a detailed review on the geotechnical properties (Chung et al. 2001), some special testing sites called reference testing sites, were proposed by the BK21 project, Dong-A University, taking into account the following considerations:

1) A reference testing site is a location at which geotechnical testing is performed in such a way that geotechnical properties of the Pusan clays can be reliably obtained and can be considered as the reference values not only for that site but also for the vicinity areas.

2) When dealing with a reference site, one should review carefully the shortcomings of previous investigations and try to make improvements. Soil disturbance due to drilling and sampling technique, characteristics of the samplers in use, low values of preconsolidation pressure and overconsolidation ratio, applicability of field vane shear and piezocone tests are just some of the typical issues for Pusan clays that need to be carefully looked into.

3) At the reference testing site one can try to apply any new testing technique that may have a potential usefulness for investigation of Pusan clays in the future. Easy access to the site for a subsequent re-testing should be regarded as one of important criteria in its selection.

Five sites were selected, as shown in Fig. 1 and, testing work at these sites has been steadily carried out since early 2000. In the following parts of this paper, the testing results obtained at the Jangyu site are processed and analyzed.

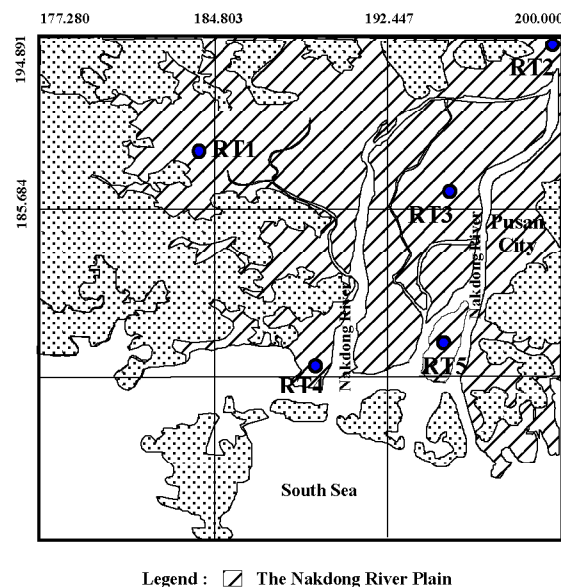


Fig. 1 Five reference testing sites (RT1: Jangyu; RT2: Yangsan; RT3: Kimhae; RT4: Shinho; RT5: Eulsookdo)

CHARACTERIZATION OF PUSAN CLAYS AT JANGYU SITE, PROPERTIES IN THE REMOULDED STATE

The location of the Jangyu site can be seen in Fig. 1. A general soil section is shown in Fig. 2, showing the clay layer is thickening eastward, from 14 m to 35 m. On top of the soil profile there is a weathered clay layer about 3 or 4 m thick, then comes the soft clay layer, which is underlain by a sand and gravelly sand layer, which in turn overlies the weathered bedrock.

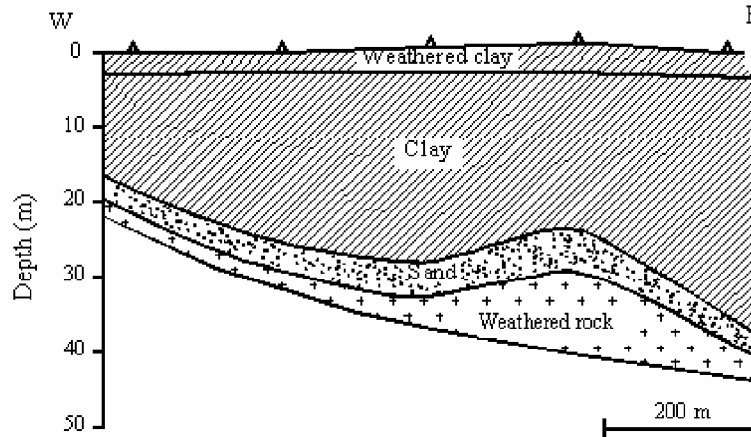


Fig. 2 Soil section at Jangyu site (Chung et al. 2001)

Atterberg Limits and Other Index Properties

The basic geotechnical properties were averagedly evaluated based on the testing results from five boreholes at the Jangyu site. There are presented in Fig. 3. The clay deposit at this site can be separated into three units, i.e., 0 - 4 m, 4 - 18 m, and 18 - 34 m. The top 3 or 4 m of soil consists of weathered clay with a plasticity limit about 22%, a liquid limit about 60%, and a water content about 45 to 50%. The 4 - 18 m layer consists of a very soft clay, which has a plasticity limit about 25 to 30%, a liquid limit of 60 to 70%, and a water content exceeding the liquid limit of about 90%. The 18 - 34 m layer consists of soft clay, which has a plasticity limit about 20%, a liquid limit of about 50 to 55%, and a water content that is almost the same as the liquid limit. The liquidity index of the upper part, from 0 to 18 m, is between 1.5 and 2.0, but that of the lower part of the clay deposit is typically around 1.0.

From the plasticity chart in Fig. 4, it can be seen that the upper clay layer is more toward the CH type, while the weathered layer and the lower layer are more toward the CL type. The relationship between water content and liquid limit are shown in Fig. 5. Again, one can see that the upper and lower clays are somewhat differentiated by the liquidity index, the lower clay having a liquidity index of almost 1.0, typical for a tidal flat deposit, while the liquidity of the upper clay is higher, at about 1.5, more toward a seabed environment. Both salinity and organic content, shown in Fig. 6 and Fig. 7 respectively, support the separation between the upper and lower clay layers. The upper clay has a higher organic content (from 5 to 8%) and salinity (from 1.5 to 3 ‰), while the lower clay has a lower organic content (from 3 to 5%) and salinity (from 1.0 to 1.5 ‰). If one looks back at the grain size and unit weight profiles in Fig. 2, it can be seen that the grain size distribution shows a rather uniform fraction throughout the clay deposit, which is of less than 5% of sand, 55 to 60% of silt, and around 40% of clay. On the other hand, the unit weight profile supports the separation of the clay deposit into three sub-layers, i.e., the weathered clay, with unit weight of 1.65 to 1.7 t/m³, the

upper very soft clay, with unit weight of 15 kPa, and the lower soft clay, having a unit weight mainly from 16.5 to 17 kPa.

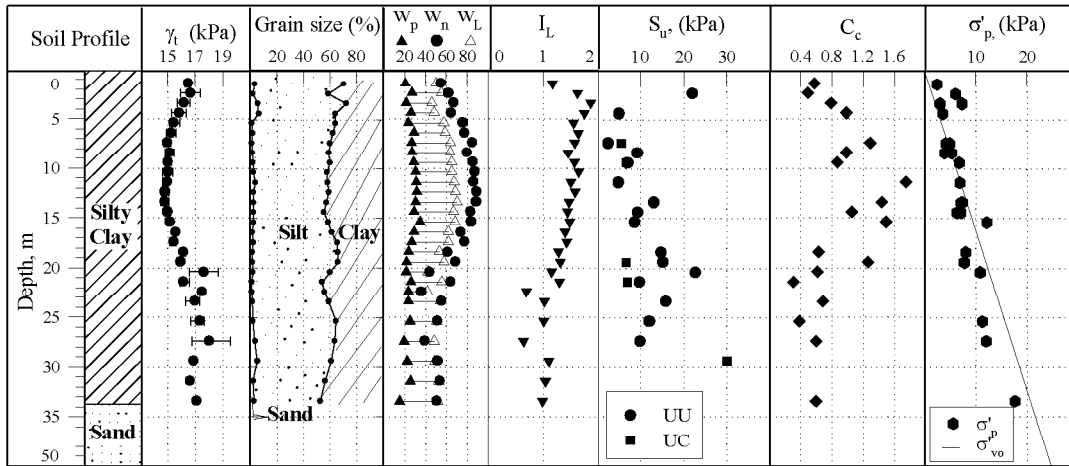


Fig. 3 Basic geotechnical properties at Jangyu site

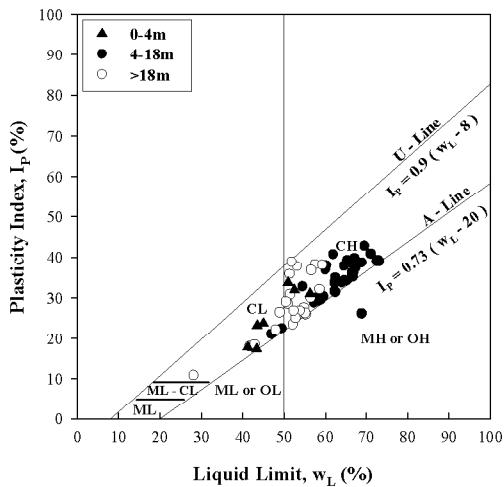


Fig. 4 Plasticity chart

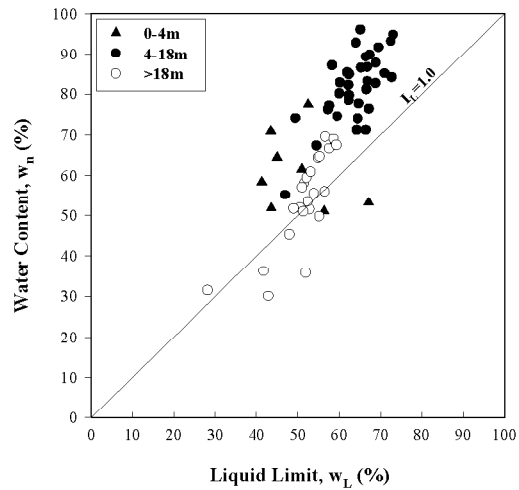


Fig. 5 Water content vs. liquid limit

Activity

Activity, defined as the ratio between the plasticity index, I_p , and the clay fraction (taken as less than $2 \mu m$) is plotted against clay fraction in Fig. 8. The activity of Pusan clays at the Jangyu site varies mainly from 0.38 to around 1.25. As seen from Fig. 8, the predominant mineral is illite, which has a typical activity of 0.9, while kaolinite is a minor component with a typical activity of 0.38.

Friction Angle in the NC Range

Friction angles determined in the normally consolidated range (ϕ'_{nc}) from triaxial tests were used. They are shown in Fig. 9 as a function of the plasticity index. The data obtained were few and rather scattered for this Jangyu site. Consequently, a general decreasing trend of

ϕ'_{nc} as the plasticity index increases, similar to the one proposed by Bjerrum and Simons (1960), could not be observed.

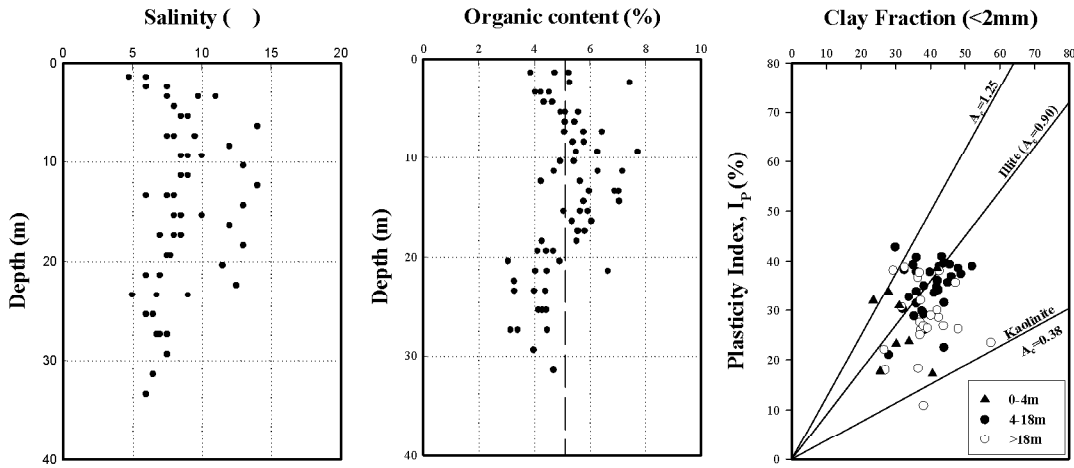


Fig. 6 Salinity content

Fig. 7 Organic content

Fig. 8 Activity chart

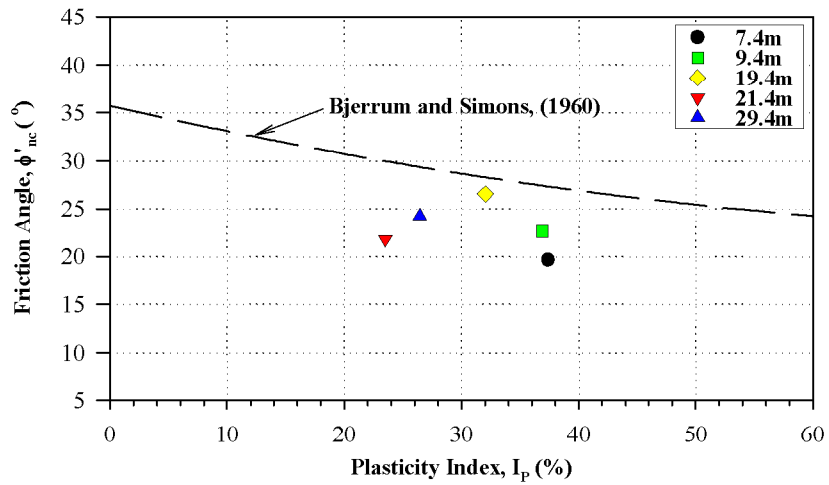


Fig. 9 Friction angle in the NC range versus plasticity index

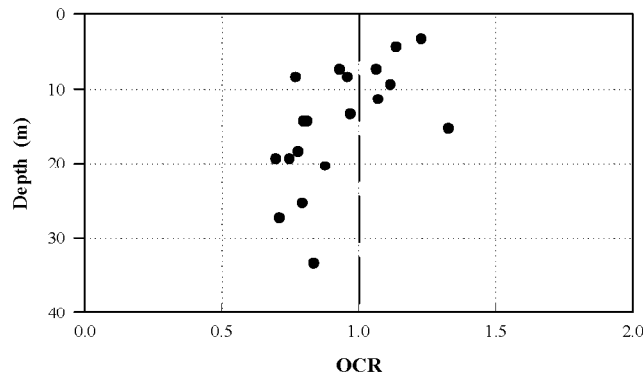


Fig. 10 OCR values from oedometer tests

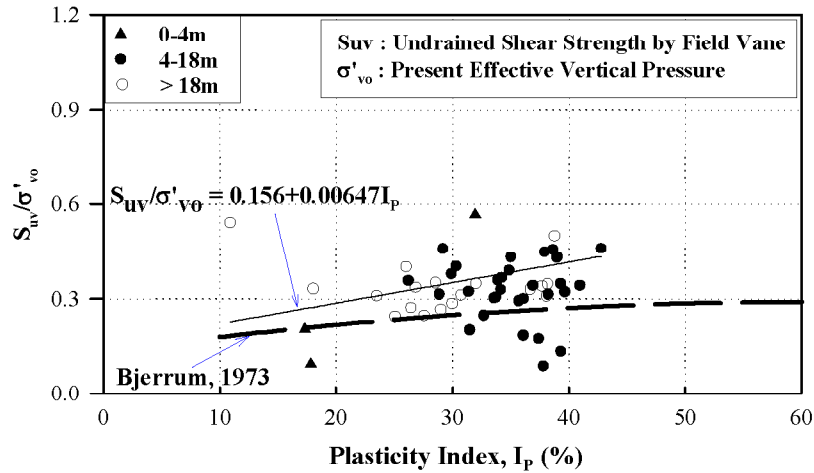


Fig. 11 Relationship between S_{uv}/σ'_{v0} and plasticity index

PROPERTIES IN THE INTACT STATE

Preconsolidation Pressure and Overconsolidation Ratio, OCR

The preconsolidation pressure was determined based on conventional oedometer tests, performed on samples taken with the NX (76.2mm) sampler. The OCR of clays at Jangyu site are shown in Fig. 10, they decrease with depth, reaching values as low as 0.7 at depths larger than 12 m.

Undrained Shear Strength from Vane Shear Test

In Fig. 11, the ratio S_{uv}/σ'_{v0} is plotted versus plasticity index. A correlation similar to that found by Bjerrum (1973) was not obtained, however an increasing trend of S_{uv}/σ'_{v0} as plasticity index increases was observed. The undrained shear strength values, unconfined compression (UC) and field vane (FV) tests are presented versus depth in Fig. 12; they show an increasing trend with depth from 10 kPa at 4 m to 50 kPa at 30 m.

Piezocone

In Fig. 13, results of CPTU tests including the corrected total cone tip resistance (q_t), excess pore pressure (u_2) and sleeve friction (f_s) at five boreholes, SB10, SB12, SB14, SB20 and SB23, are plotted. On the q_t profiles the clay layer and its upper section of weathered clay are well identified. However separation of the clay deposit into upper and lower sublayers by q_t is not clear, which is probably better seen in the u_2 and f_s profiles. A piezocone-based lithology parameter (N_g), proposed by Giao et al. (2001), was calculated. The N_g profiles are shown in Fig. 13 and they also support the separation of the clay deposit.

The classical cone factor, N_{kt} , relates the net cone tip resistance ($q_t - \sigma_{v0}$) to undrained shear strength (by field vane in this case) by the following equation:

$$(q_t - \sigma_{v0}) = N_{kt} \cdot S_u \tag{1}$$

where q_t is the cone tip resistance, σ_{v0} is the total stress, and S_u is the undrained shear strength. The cone factor of 10.82 was determined for the entire clay layer as shown in Fig. 14, this value being similar to that obtained for the Yangsan site by Tanaka et al. (2001). For three sublayers, 0-4 m, 4-18 m and 18-34 m, the cone factor was calculated as 19.84, 16.4 and 10.61, respectively.

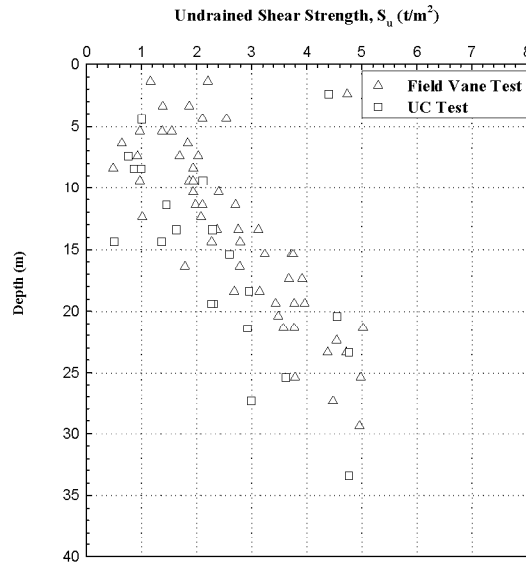


Fig. 12 Change of undrained shear strength with depth

PROPERTIES ASSOCIATED TO THE PASSAGE FROM INTACT TO REMOULDED STATE

Intrinsic Compression

The concept of intrinsic properties was introduced by Burland (1990), referring to the compression properties of clays which are reconstituted at a water content of about 1.25 liquid limit, without any air-drying or oven-drying, and then consolidated. According to Burland, one can compare natural properties of clays to the intrinsic properties for their classification. On the basis of analysis of compressibility and shear strength of natural clays, he suggested a new soil parameter, the void index, I_v , defined by the relation:

$$I_v = \frac{e - e_{100}^*}{e_{100}^* - e_{1000}^*} = \frac{e - e_{100}^*}{C_c^*} \quad (2)$$

where e_{100}^* and e_{1000}^* are void ratios at consolidation pressures of 100 and 1000 kPa respectively, obtained preferably by one dimensional compressibility tests on reconstituted clays, and C_c^* is the intrinsic compression index. In Figs. 16-17, intrinsic compression lines (ICL) and sedimentation compression lines (SCL) were plotted. ICL represents a relationship between a parameter called the void index (I_v) and loading pressure (σ'_v) as obtained on reconstituted clays, while SCL represents a relationship between a parameter called the void index (I_{v0}) and the effective overburden (σ'_{v0}) as deduced from many natural soft clay deposits. These two curves can be used as references for evaluating the degree of structuration of natural clays. (I_{v0} , σ'_{v0}) data are plotted in Fig. 16. It can be seen that most of the points are

above the SCL line, indicating that the clays at Jangyu are quite structured. Burland (1990) indicated that for normally consolidated clays whose natural states are close to or above the SCL, the post-yield oedometer compression curve is steeper than the SCL, and it will cross the SCL to converge towards the ICL, which is exactly what happens to Pusan clays at the Jangyu site as seen in Fig. 17.

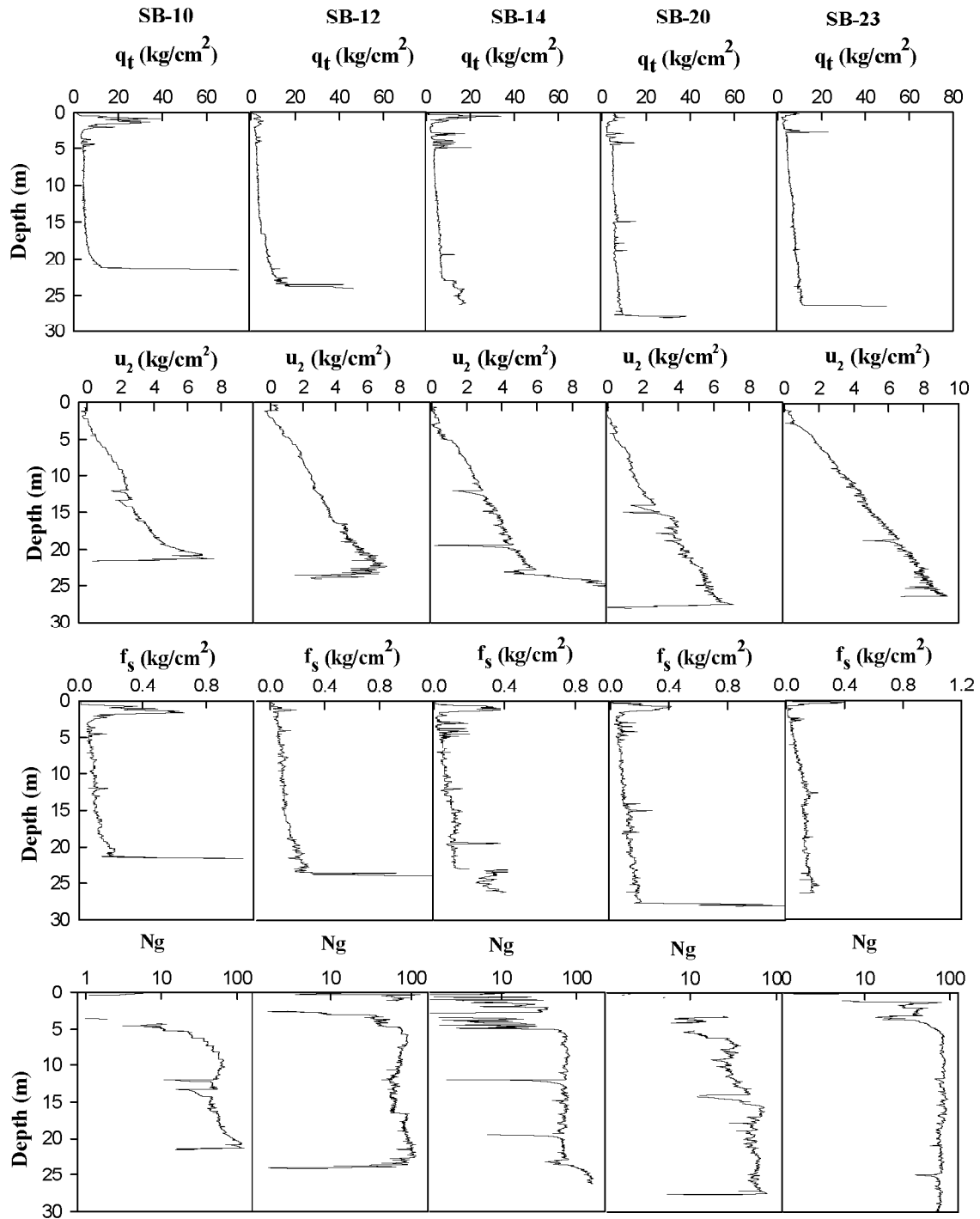


Fig. 13 Results of CPTU tests

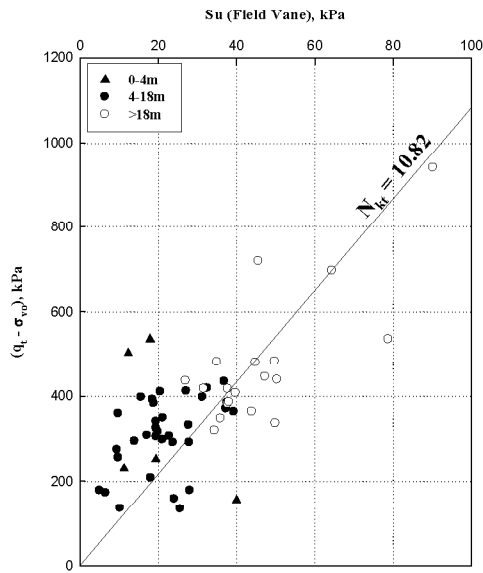


Fig. 14 The lumped cone factor

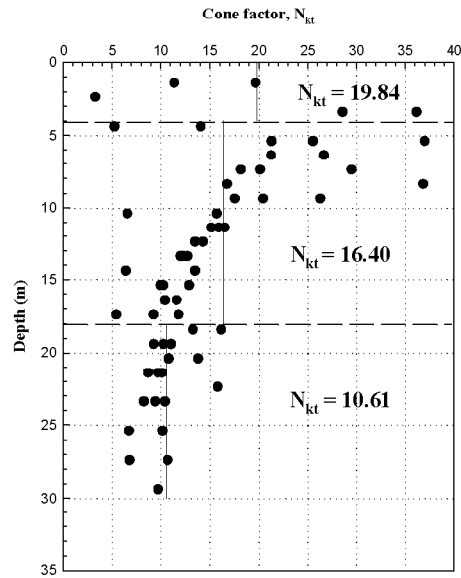


Fig. 15 N_{kt} for each individual sub-layer

According to Nagaraj (2000), for saturated clays, there exists a unique relationship between the effective stress and void ratio at equilibrium condition when compressed. In Fig. 18, an intrinsic state line was constructed using the equation suggested by Nagaraj, as follows:

$$\frac{e}{e_L} = 1.23 - 0.28 \log_{10} \sigma'_{v0} \quad (3)$$

The intrinsic state line in Eq. (3) represents a reference state, which indicates the normalized compression curve of remolded clays. The e_0/e_L vs. σ'_{v0} points are plotted in Fig. 18, where e_0 is the in-situ void ratio, e_L is the void ratio at liquid limit water content state and σ'_{v0} is the effective overburden. Figure 18 shows that the ratio e_0/e_L is from 0.8 to 1.6, corresponding to a range of effective overburden from 10 to 110 kPa. It can be seen that the points lie well above the ISL, thus the clay here is structured and essentially an NC cemented clay according to Nagaraj's classification.

Sensitivity

The sensitivities of Pusan clays were determined based on the field vane (FV), fall cone and unconfined compression (UC) tests as shown in Fig. 19. At Jangyu, the sensitivity changes from 2 to 12. The field vane tests gave sensitivities smaller than those obtained from UC and fall cone tests. The former are in the range of 2-6, while the later are in the 8-12 range.

Compression Index

The compression index, which was obtained in the range between σ'_{v0} and $2\sigma'_{v0}$, is plotted versus the natural void ratio in Fig. 20. The following correlation was obtained for these two parameters:

$$C_c = 0.83e_0 - 0.72 \quad (4)$$

In Fig. 21, the compression index is correlated to the liquid limit by the following relationship:

$$C_c = 0.035LL - 1.16 \quad (5)$$

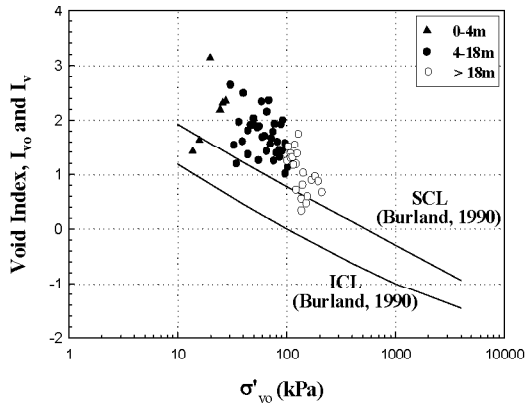


Fig. 16 Intrinsic compression of soft clays at Jangyu, based on Burland (1990)

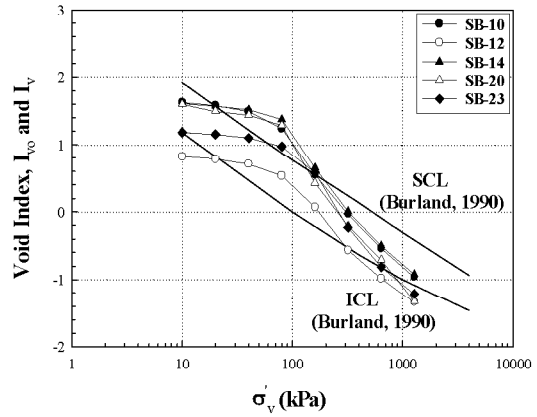


Fig. 17 Intrinsic behaviour of post yield compression curves

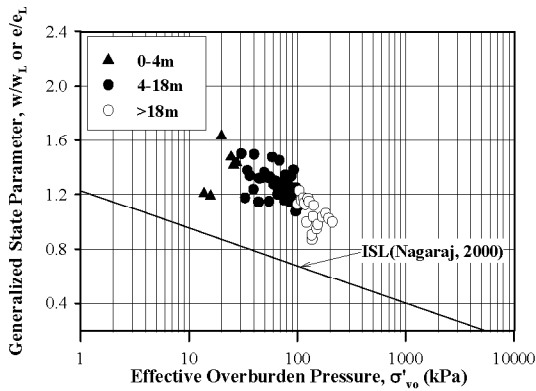


Fig. 18 The intrinsic state line (Nagaraj 2000)

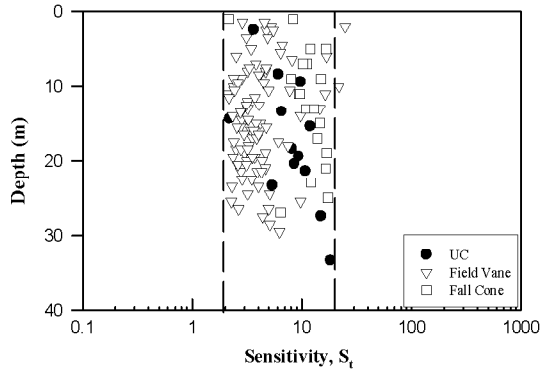


Fig. 19 Sensitivity of clays at Jangyu

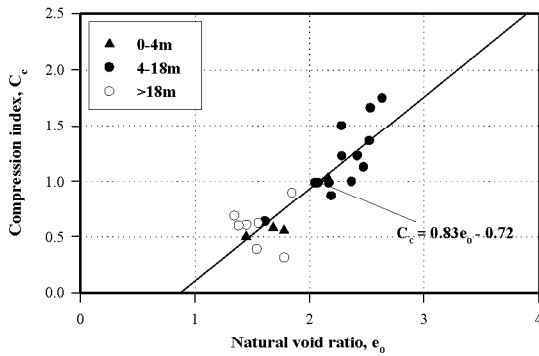


Fig. 20 $C_c - e_0$ relationship

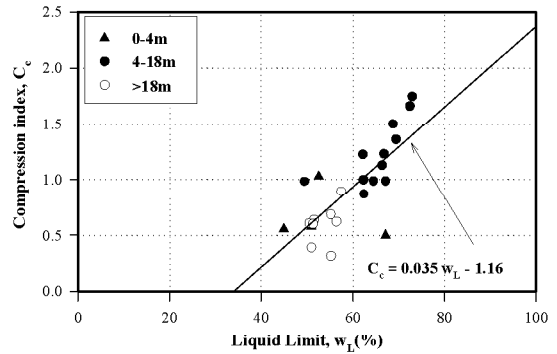


Fig. 21 $C_c - LL$ relationship

DISCUSSION ON SOME PARTICULAR CHARACTERISTICS OF PUSAN CLAYS

Effect of Artesian Pressure on Pore Pressure inside the Clay Layer

The possible influence of artesian pressure from the underlying sand layer onto the pore pressure profile of the clay layer was investigated using standpipe piezometers. At Jangyu, three piezometers were installed at 5, 15 and 25 m. Each piezometer was installed in an individual borehole of 76 mm diameter. The standpipe piezometer comprised a low-air-entry ceramic tip connected to the ground level by a PVC pipe of 25 mm inside diameter. The piezometer tip had a 26 mm diameter and was 0.8 m length. The borehole was drilled first, and then the piezometer tip was pushed from the borehole bottom to the design depth level. Shortly after installation, the standpipe piezometers were flushed by means of an air compressor, and the readings of water level inside the rising tube were taken.

The rising head inside each standpipe piezometer, and the profile of pore pressure recovery with time since its installation are plotted in Figs. 22 and 23, respectively. Fig. 22 shows that the time lag, which is the elapsed time for the head inside the standpipe piezometer to become stabilized, is about 2 weeks for the piezometers installed in the upper, very soft, clay layer, at 5 and 15 m, and about 3 weeks for the piezometer installed in the lower clay layer, at 25 m. Compared to London clays, in which stabilization had taken place in about 6 months (Dixon and Bromhead 1999), the soft clays at Jangyu clearly have a higher insitu hydraulic conductivity. The profile of pore pressure with depth in Fig. 23 does not change much after about 3 weeks, and more than that, they do not show any excess pore pressure which would make the total pore pressure within the clay deposit higher than the hydrostatic pressure. Consequently, a higher pore pressure in the clay layer due to artesian pressure from the underlying sand layer, which would imply a smaller effective stress and hence a smaller overconsolidation ratio, was not confirmed by standpipe piezometer results at this Jangyu site.

Investigation of Underconsolidation of Pusan Clays Using Piezocone Data

A piezocone tip of the u_2 type was used in CPTU tests at the Jangyu site. As the piezocone tip may be more sensitive to excess pore pressure due to unconsolidation if any in comparison with the responses from standpipe piezometers, it is of interest to exploit CPTU data for this purpose. Underconsolidation of soft marine clay in Osaka bay was investigated by Tanaka and Sakaghami (1989), based on a relationship between Δu and $(q_T - \sigma_{v0})$. Their technique was applied to Pusan clays by Giao et al. (2001). The main idea underlying Tanaka and Sakaghami's techniques is that underconsolidated clays would have higher excess pore pressure than NC clays in the same soil profile, hence they would be lying above the NC clay line which was defined as $\Delta u = 0.75(q_T - \sigma_{v0})$ for Osaka bay clays, according to the authors. Data from four CPTU boreholes are separately plotted for the upper and lower clay layers at Jangyu site and shown in Fig 24, where one can see that the points are found both above and below Tanaka and Sakaghami's line. It is interesting to observe that the points belonging to the lower layer are mostly above the line, and the points belonging to the upper layer are mostly below the line, which may suggest the former are less consolidated compared to the latter. Taking into account the fast change in values of pore pressure piezocone data as well as in soil type in a deltaic deposit, it is understandable that a single line like the one mentioned above would not be always a good criterion of separation. As an attempt of improvement, instead of a line, a band bounded between two lines, i.e., $\Delta u = 0.75(q_T - \sigma_{v0})$ and $\Delta u = 0.75(q_T - \sigma_{v0}) - 110$, was proposed by Giao et al. (2001). But in general, the method suggested by Tanaka and Sakaghami (1989) for Osaka soft clay did not prove to be an effective means of giving an answer in the case of Pusan clays.

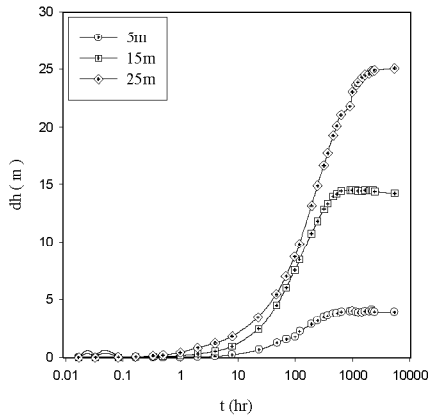


Fig. 22 Head stabilization in standpipe piezometers

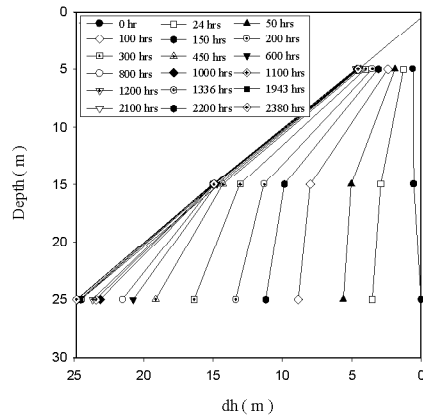


Fig. 23 Recovery of pore pressure profile in the clay layer

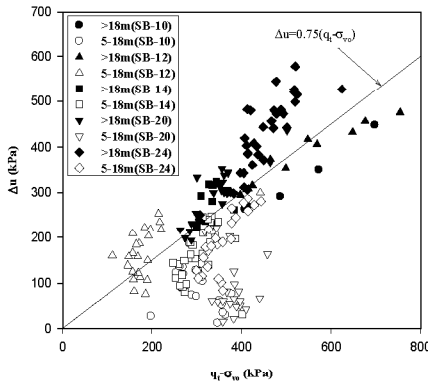


Fig. 24 $\Delta u - (q_t - \sigma_{v0})$ relationship

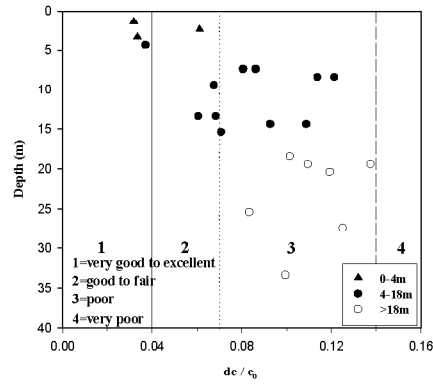


Fig. 25 Soil disturbance by Lunne et al. (1997)

Low OCR

The question of low OCR of Pusan clays has not got a clear-cut answer so far. This is mainly due to the fact that the determination of representative preconsolidation pressure values is not yet satisfactory. Various possibilities have been proposed to explain the low OCR values as follows (Kim 1999; Tanaka et al. 2000; Chung et al. 2001): (i) the possibility of artesian pressures or underconsolidation of some Pusan clays that would make the in situ vertical effective stress smaller than assumed. This hypothesis however was not confirmed in this study; (ii) some disturbance due to the sampling technique use, i.e., using the Japanese sampler that has given very good results on several sites in the world (Tanaka and Tanaka 1999), on a site at Yangsan, Tanaka et al. (2001) found preconsolidation pressure generally larger than those reported in the previously mentioned studies; (iii) the testing method also can cause low values of OCR. Tanaka et al. (2001) indicated that the preconsolidation pressure determined from a conventional oedometer test are definitely lower than those obtained from a CRS test.

Even though oedometer tests were done carefully at Jangyu, the low value of OCR persists (see Fig. 10). Soil disturbance at the site was evaluated according to a method suggested by Lunne et al. (1997) for low plastic Norwegian clay as shown in Fig. 25. The results show that most samples subjected to conventional oedometer tests were of poor quality and at greater depths there was more soil disturbance. The reasons for low OCR are interpreted to be as follows: soil disturbance due to sampling, which implies a determination of low

preconsolidation pressure; the lower quality of the specimens taken at the ends of each sampling tube; the lower quality of samples taken at great depths in which stress relief may play an important role; the conventional oedometer test itself is prone to give low values for preconsolidation pressure for a soft cemented and sensitive clay like the Pusan clays.

CONCLUSIONS

1) Five reference sites have been set up and tested since the early 2000 by the Brain Korea 21 project, Dong-A University, as an additional measure to help improve characterization of Pusan clays in the Nakdong deltaic plain.

2) The testing works at Jangyu site (Fig. 1) were the first ones to be completed, allowing a detailed examination of Pusan clays at this site. Characterization of the clay was done, using a format used by Leroueil (1999), in which the geotechnical properties are grouped into three categories, corresponding to the intact, remoulded and transitional states. The soft clay at the Jangyu site is probably the softest among Pusan clays (Chung et al. 2001). It is of CH-CL type and is classified as a normally consolidated type. The clay deposit can be separated into three units, i.e., about 3 or 4 m of weathered clay on top, followed by a 4-18 m layer of very soft clay having a water content exceeding the liquid limit, and then a soft clay layer having a water content near the liquid limit. It was observed that where the bedrock depth is shallow the lower clay sublayer is absent, and the upper very soft clay layer is overlying directly on the bedrock. This stratification was supported further by piezocone data.

3) The application of the intrinsic compression concept (Burland 1990; Nagaraj 2000) showed that the clays are soft-cemented and structured.

4) The results of pore pressure monitoring from the standpipe piezometers did not support the hypothesis on the influence of artesian pressure from the underlying sand layer on the pore pressure distribution inside the clay layer, which would cause low values in effective stress and overconsolidation ratio. An additional study on underconsolidation was done based on piezocone data following a method suggested by Tanaka and Sakaghami (1989) for Osaka soft clays as shown in Fig. 24. Although it was interesting to observe that the data related to the lower clay layer are mainly lying above and data related to the upper clay layer are mainly lying below the line $\Delta u = 0.75(q_t - \sigma_{v0})$, which is supposed to separate the underconsolidated state (above) from the normally consolidated state (below), it is recommended that a similar study be carried out further for the other sites until a more definitive answer to the problem can be found.

5) The factors causing low values of the preconsolidation pressure are not yet clearly understood. One can say that soil disturbance due to drilling, sampling and testing methods have contributed significantly to low values of preconsolidation pressure, hence causing the OCR to be as low as 0.7. But even with a good quality sampler of the Japanese type or by means of CRS consolidation tests (Tanaka et al. 2001) the OCR values still remain low, just around 1.0, while for a normally consolidated clay like the Pusan clays, an OCR of slightly higher than 1.0 is usually expected. The lower quality of sub-samples taken toward the ends of a sampling tube or of the samples taken from a depth of about 12 m or more need to be quantitatively evaluated.

6) The investigation at a reference testing site has demonstrated the benefits of geotechnical study of Pusan clays. Some difficulties regarding promotion or setting up of a reference site are: availability of land reserved only for geotechnical testing purpose; duration of time in which the site would remain accessible; funding for geotechnical testing which is purely for research purposes. The tests at Jangyu site were not all perfectly done, and continuing efforts must be pursued for a better understanding and characterization of Pusan

clays. However, the concept of a reference testing site proved somewhat useful for investigation and characterization of the clays. Hopefully, it can evolve in such a way as to truly become a valuable addition to approaches to site investigations in the Nakdong river plain.

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