Anisotropic Permeability Evaluation of Pusan Clays at the New Pusan Port
부산신항에서의 부산점토에 대한 투수 이방성에 대한 평가

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SYNOPSIS : 1990년 이래 낙동강 하구 서쪽지역인 서부산과 인근 지역에서는 대단위 지반조성공사가 수행되었다. 이 지역에서는 부산점토라고 명명된 점성토가 20-70m의 두께로 상당히 두텁게 형성되어있다. 최근에 들어 정교한 지반조사가 수행됨에 따라 이 지역의 점토에 대한 공학적 특성이 효과적으로 밝혀졌지만, 점토의 특성을 면밀히 규명하기 위해서는 여전히 많은 과제가 남아있다. 본 논문에서는 부산신항 지역에서 점토에 대하여 다양한 방법으로 투수계수를 구하여 투수특성을 규명하고자 한다. 이를 위하여 수평 및 연직방향의 배수에 의한 일정변형률(CRS) 압밀실험, 표준압밀실험 및 압밀 중에 변수위 투수실험이 실내실험으로 이루어 졌으며, 현장실험으로 CPTU에 의한 소산실험 및 Casagrande형 피에조미터에 의한 소산실험이 실시되었다. 이들 결과를 서로 비교하여 합리적인 실험결과를 분석하며, 이 점토에 대한 깊이별 투수계수 및 투수 이방성을 규명하고자 하였다.

Key words : clay, permeability, anisotropy, laboratory test, in-situ test

1. Introduction

Since the early 1990s, a huge reclamation project was proposed to build for a new Busan port, a key belt of industrial and residential complexes, etc in the Nakdong River Estuary, South Korea. The area is covered with thick clay deposits, or so-called Pusan clays, varying from 20 to 70m in thickness. Despite a large number of geotechnical investigation that have been carried out for the clays, the local geotechnical engineers have been unable to successfully deduce the geotechnical properties due to some problems relating sample quality, the application of in-situ tests, and others (Chung and Giao, 2001). Particularly, they have seldom performed any specific tests, even although vertical drains with preloading have been adopted for the projects. Therefore, it is extremely necessary to get the consolidation characteristics considering horizontal drainage as well as vertical drainage for the clays. Some soils are often anisotropic in both their mechanical properties and their permeability. The causes of this anisotropy include the one dimensional stress history that they may have experienced in being deposited over areas of large lateral extent, and seasonal variations in the intensity and nature of depositional processes, which may lead to vertical variation in the particle size distribution of the soil. A small change in permeability results in an inordinately large change in the progress of consolidation and that the magnitude of this effect increases with the thickness of a soil deposit. The researchers also emphasized that the use of distilled water in permeability tests may have an adverse effect on the hydraulic conductivity of soils.

In this paper, the permeability evaluated by laboratory tests conducted with same salinity water and field test are presented. The laboratory tests are included constant rate of strain consolidation with vertical and radial drainage, standard oedometer tests, and some direct measurements of permeability using either vertical or radial drainage. The in situ tests included the piezocone and the piezometer.

2. Site Investigations

2.1 Sampling methods

Figure 1shows location map of soil sampling and in situ tests. The advanced sampling techniques were adopted with different core tubes, samplers and fixed piston types for the upper and lower clays. Particularly for the lower stiff clay, the rod extension fixed piston sampler has been applied. The samplers were withdrawn carefully from the bore hole and were sealed immediately with paraffin wax for about 30mm thick on either end. The samples taken were carefully wire trimmed into specimens for testing in the laboratory. All tests were conducted using the remained part of sample except of the top 30cm and the bottom 10cm of the sampling tube sample.

2.2 Geology at the study area

The study site was chosen in the construction area of Pusan new port. As reported by Chung et al. (2004), soil stratification on Pusan clays could be successfully understood by geological investigation and CPTU test. The geological characteristics are closely related to the relative changes in sea level and geographical features of the site. The deposit largely consists of (upper) soft and (lower) stiff clays. Probably, the upper layer has the depositions since the period of re-transgression and the latter prior to the time of upper layer. The location of sampling and field tests is N-1 in Fig. 1.

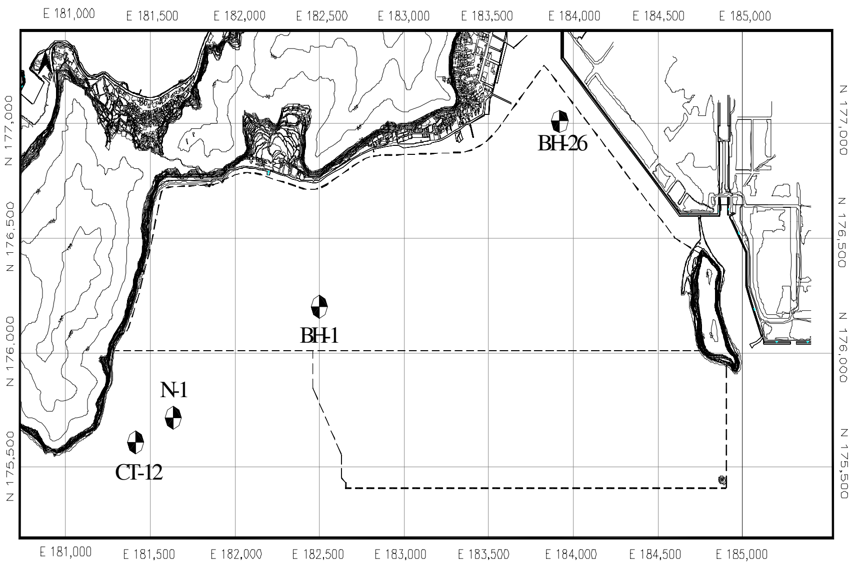

Fig. 1 Location of Sampling (N-1)

2.2 Basic geotechnical properties

Fig. 2 presents basic geotechnical properties for each depositional environment evaluated by the results of geological investigations and CPTU test. Generally the physical indices change depending upon the depositional environment for each layer. The upper layer contains clay (< 2 ㎛) of about 40% and sand of less than 5%, but the lower layer has clay in smaller quantities and higher sand contents.

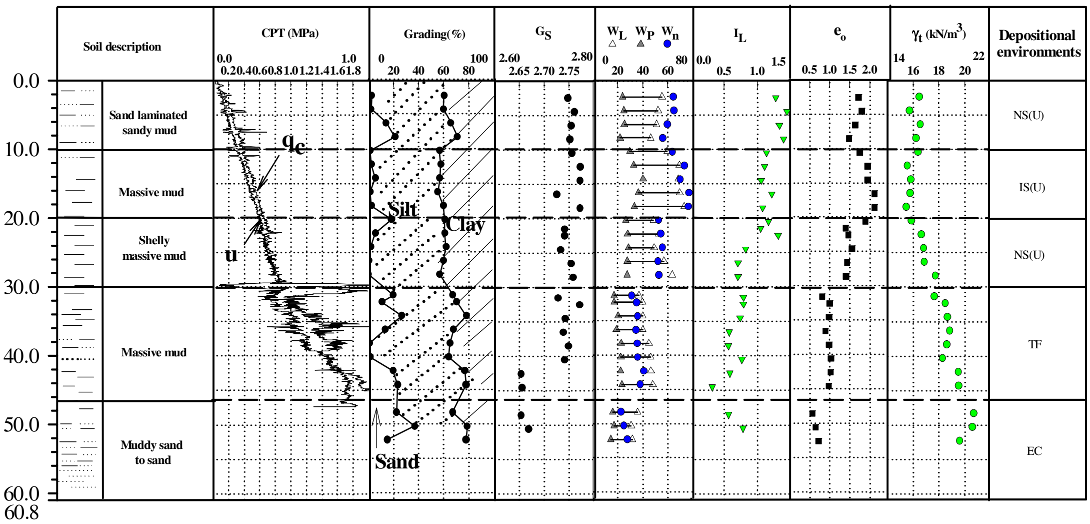

Fig. 2 Basic Geotechnical properties

3. Indirect Evaluation of Permeability

It is well accepted that the consolidation should not be based on the coefficient of consolidation or the degree of consolidation, but on permeability. Since consolidation tests are routinely performed in geotechnical engineering it was logical to consider using the observation of rates of consolidation as a mean of indirectly evaluating the permeability of natural clays in their initial condition e_0, σ'_{v0} or under decreasing void ratios. Three types of consolidation tests are performed for indirect permeability evaluation: the conventional IL test and the constant rate of strain tests (CRS) with vertical and horizontal drainage conditions.

3.1 Test with radial outward drainage (CRS RO)

A constant rate of strain consolidometer with radial drainage (CRSRO) developed at the Seoul National University of Korea and established equations based on Barron's equal strain theory (1948) to determine the horizontal coefficients of consolidation and permeability under radial flow conditions. For CRS tests with radial drainage the horizontal coefficient of consolidation is given by:

$$C_h = \frac{k_h}{m_v \gamma_w} = \frac{R^2}{4u_c}\frac{\Delta\sigma'_v}{\Delta t} \qquad (1).$$

By the pore water pressure distribution, the average effective vertical stress can be expressed as:

$$\sigma'_{v.ave} = \sigma_v - 0.5u_c \qquad (2)$$

where $\sigma'_{v,ave}$= average vertical effective stress, σ_v= total vertical stress, u_c= excess pore water pressure at the undrained bottom boundary, C_h= coefficient of consolidation for radial drainage, k_h= coefficient of permeability, γ_w= unit weight of water and m_v = coefficient of volume of compressibility. One problematic aspect of CRS testing is selecting an acceptable rate of loading. If tests are run too slowly, then appreciable secondary compression strains will occur. If tests are run too fast, high excess base pore pressure will lead to significant variations of void ratio and effective vertical stress in the specimen. Mesri and Feng (1992) gave recommendations for selecting an appropriate strain rate that gives practically the same compression curve as the EOP curve from IL tests. In present study the rate of strain was selected to have no base excess pore pressure during loading (EOP) in IL tests. The horizontal coefficients of permeability from the CRSRO tests are plotted in Fig. 3. Although the k_h values decrease gradually in the overconsolidation range, they decrease much more rapidly in the normal consolidation range due to larger changes in void ratios.

3.2 Test with vertical drainage

CRS oedometer tests were conducted using the Rowe cell of GDS instrument. The data were reduced using the non-linear CRS theory of Wissa et al. (1971). Fig. 4 shows the results of k_v against effective stress. The k_h and k_v values from Figs. 3 and 4 are well consistent by the Seah et al. (2004). Fig. 5 provides a comparison of the permeability obtained from the CRS tests. In Fig. 6 comparisons are made in terms of stress rather than void ratio. The k_h/k_v ranges averagely from 3.0 to 5.0 for the upper marine clay and is about 1.20 to 1.50 for lower clay. These values are slightly higher than those expected for uniform clays and seem to be more appropriate for stratified clays. This may be due to the presence of some sand laminations of more permeable materials. k_h at 2m in depth and k_h and k_v at 38m and 44m depths are relatively high because of sand laminations.To better appreciate the degree of anisotropy, the permeability measured in samples subjected to horizontal and vertical flow is compared in Fig. 6.

3.3 Piezocone dissipation test

Dissipation test by means of piezocone is generally used for evaluating the flow characteristics of in situ soil. Fig. 7 shows the permeability profile with depth determined using the four methods: Torstensson (1997), Baligh and Levadoux (1986), Gupta and Davidson (1986), and Teh and Houlsby (1991). The permeability shows relatively large permeability oscillations with depth, suggesting the likely presence of laminations of silty sand material. The four methods provide parallel trends of permeability $k_h$with depth, only differing in terms of absolute values. The highest of these is due to the method of Baligh and Levadoux (1986) and the lowest to the methods of Gupta and Davidson (1986) and Torstensson (1977), differing by a ratio of about four. This difference is mainly because the influence of rigidity index I_r. The k_h value obtained using Teh and Houlsby (1991) agrees better with laboratory measurements in general. A similar conclusion has also been made by Danziger et al. (1997). For the sake of comparison, Fig. 7 also sketches the horizontal permeability determined from laboratory tests.

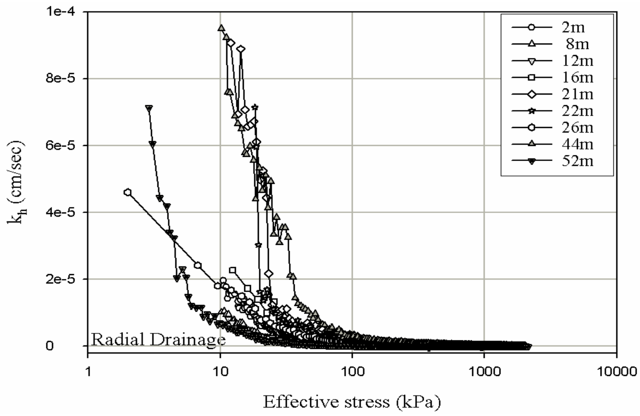

Fig. 3 Relation between k_h and effective stress

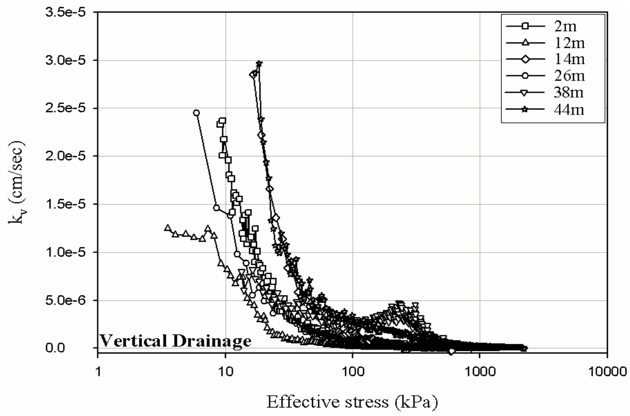

Fig. 4 Relation between k_v and effective stress

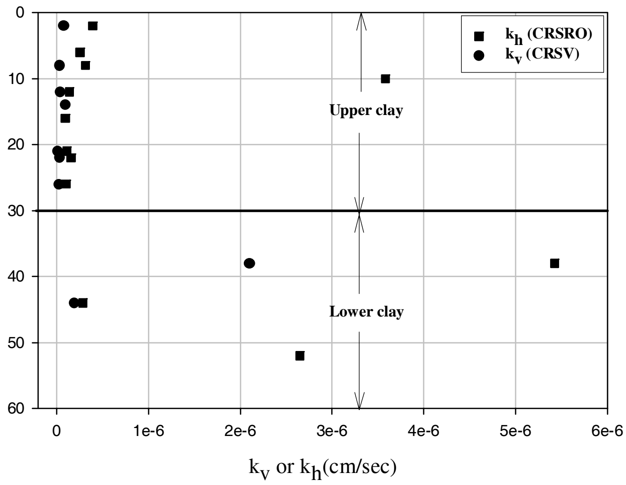

Fig. 5 Comparison of k_h and k_v profiles with depth

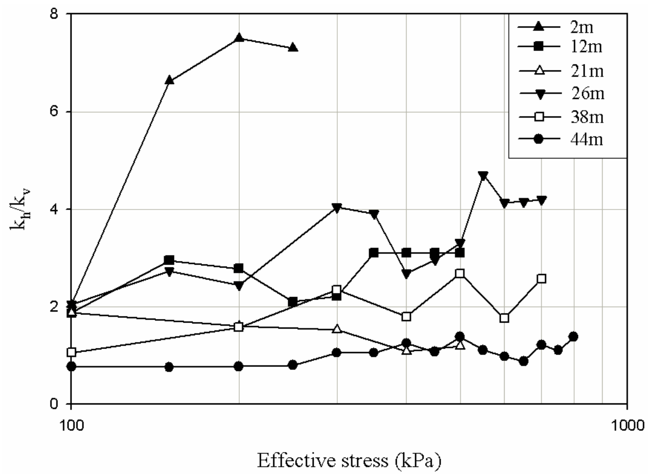

Fig. 6 Ratio of horizontal to vertical permeability (k_h/k_v) and effective stress

3.4 Piezometer test

The rising head inside each standpipe piezometer was monitored and the in situ permeability was computed by using its result (Huh 2004). The methods suggested by Hvorslev (1951) and Tavenas et al. (1986) as Equations (3) and (4) respectively used to calculate coefficient of permeability.

$$k_h = \frac{q}{\Delta h \cdot F} \quad (3)$$

$$k_h = \frac{A}{F} \cdot \frac{\ln(H_1 / H_2)}{(t_2 - t_1)} \quad (4)$$

where F = 7d+ 1.65 (for the case λ/d > 4.0), q and Δh are quantity (cm^3/sec) and head difference (cm) during the time between t_1 and t_2, H_1 and H_2 are the head at the times t_1 and t_2, A is the cross sectional area of piezometer, and d and λ are the diameter and length of piezometer, respectively. Fig. 7 shows the calculated permeability, it shows that k_h is almost same by the two methods but less than laboratory k_h values.

3.5 Empirical formulae

Another approach to evaluate permeability is empirical formula, and an empirical estimate of k_h can be directly from the t_{50} reading (Parez & Faureil 1988). This is conveniently approximated by:

$$k(cm/\sec) = (251 \cdot t_{50})^{-1.25} \quad (5)$$

where t_{50} is time elapsed to reach 50% degree of consolidation from piezocone dissipation test in seconds. In Fig. 7 also sketches the k_h from empirical formula provides reasonable estimate of permeability.

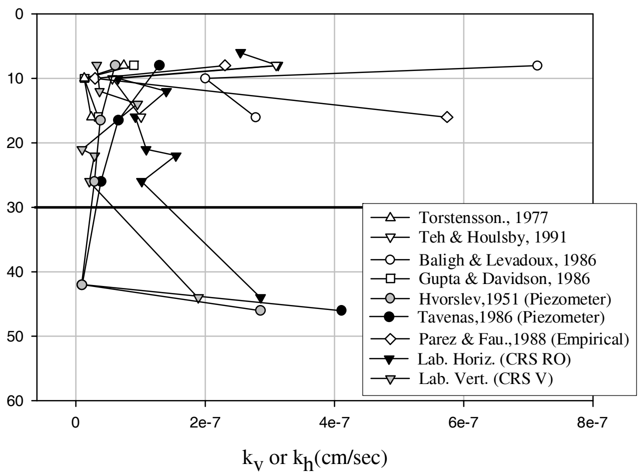

Fig. 7 Horizontal permeability obtained by the empirical formula and laboratory and field tests.

4. Direct Measurement of Permeability

The most suitable method for measuring soil permeability is represented by the measurement of water flowing into a soil sample. Falling-head tests were carried out on oedometric cells at the end of each increment loading to measure the flow rate through the soil specimen (Al-Tabba & Wood, 1987 and Tavenas et al., 1983). In present study, two types of tests were carried out to determine this parameter. One is on the vertical permeability test and the coefficient of permeability can be calculated. Another test is on horizontal permeability (k_h) with drainage is in radial direction. For this test, a modified oedometric cell was built in the Geotechnical Laboratory at the Seoul National University of Korea. The clay was able to drain radially both inwards towards the central porous column and outwards towards the porous plastic as indicated. The initial applied head difference was 400mm in all tests. The horizontal permeability k_h can be calculated from Equation 6.

$$k_h = (\frac{a}{2\pi Lt})\ln(\frac{R}{r_o})\ln(\frac{h_o}{h}) \qquad (6)$$

where r_o and R are the internal and external radii of the clay specimen and the other symbols have the meanings already given.

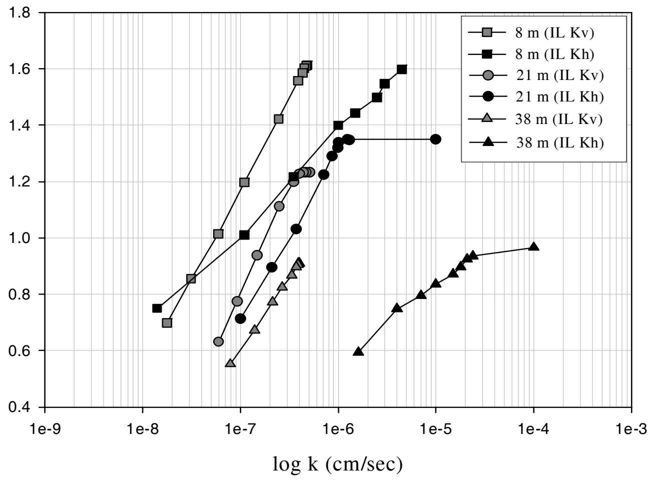

Fig. 8 Relation of e-log k by the oedometer test

The values of vertical and horizontal permeability of Pusan clay obtained from falling head tests and IL test are plotted against the void ratio in Fig. 8. It is observed that the permeability of clays are dependent on the void ratio. At a void ratio (corresponding to a vertical effective stress of about 500 kPa), the horizontal permeability is averagely about 2.5 times as large as the vertical permeability and about 6 times larger than permeability calculated from IL test. Because of radial inward and outward drainage the direct measurement of horizontal permeability is found to be slightly more than permeability from CRSRO test.

5. Conclusions

From the results of laboratory consolidation tests of CRSRO, CRSV and conventional oedometer direct and indirect tests, the Pusan clay at the New Pusan Port site is found to be anisotropic. The direct measurement of k_h is larger than those of field tests as well as CRSRO test because of combined inner and outer drainage system. It has been shown that among the various methods of determining soil permeability form dissipation tests, the more rigorous method of Teh and Houlsby (1991) gave better k_h values comparatively with laboratory results.

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