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# 낙동강 하구 지반 매립시 발생된 과다 압밀침하
# LARGE CONSOLIDATION SETTLEMENT OCCURRED DURING RECLAMATION WORKS IN THE NAKDONG RIVER MOUTH

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**요지** : 낙동강은 그 하구 근처에서 김해평야하고 부르는 델타지역을 형성하였다. 김해평야에 퇴적된 점성토는 다른 나라의 점토층에 비해 유달리 두껍다 (최대 60m). 이 지역의 일부는 새로운 공업단지의 개발을 위해 연직 배수재를 설치한 후 평균 5-7m 의 높이로 매립하였다. 연약 지반 위에 매립작업을 수행하면서 침하량을 측정하였는데, 실측침하량은 이론적으로 예측한 침하량보다 현저히 크다는 것을 알게 되었다. 이 논문은 김해점토의 퇴적환경의 관점에서 과다침하가 발생되는 이유를 기술하고 있다.

**ABSTRACT** : The Nakdong River in Korea has formed a delta area called the Kimhae plain near the river mouth. Its clay deposit is unusually thick (up to 60m) compared with the clays deposited in other parts of the world. Some parts of the area has been reclaimed with the height of approximately 5 to 7m after installing vertical drains for the development of important new industrial complexes. Settlement measurements were taken during the reclamation works on the soft ground, and it was revealed that the measured settlements were extremely higher than predicted. This paper discusses possible reasons on unusual large settlements from depositional environments of Kimhae clay.

## INTRODUCTION

The Nakdong River of Korea, flowing from the north to the southeast coast of the Korean peninsula, has deposited fines near the river mouth, and formed a wide delta area called the Kimhae plain.

Since the Korean Government planned a belt of key industrial complexes along the coastline of this delta area, reclamation works have been started after installing vertical drains on the soft ground for the new land development since the early 1990s. The areas for development of the river mouth are the Myungj residential complex, the Shinho industrial complex, and the Noksan national industrial and residential complex (see Fig. 1). A new port will be built between the Noksan industrial complex and Kaduk-do. The Yangsan-Mulgum residential complex is under construction at the north part of the Kimhae plain.

## DEPOSITION OF NAKDONG DELTAIC SOILS

In the early 1970s, the first large-scale subsurface exploration was carried out for the development of the river mouth. This was intended to find a suitable site for the second steel mill construction after the successful operation of the first one already located in Pohang. The new location of the exploration was Dadaepo area (see Fig. 1), which is just the river mouth of the main stream.

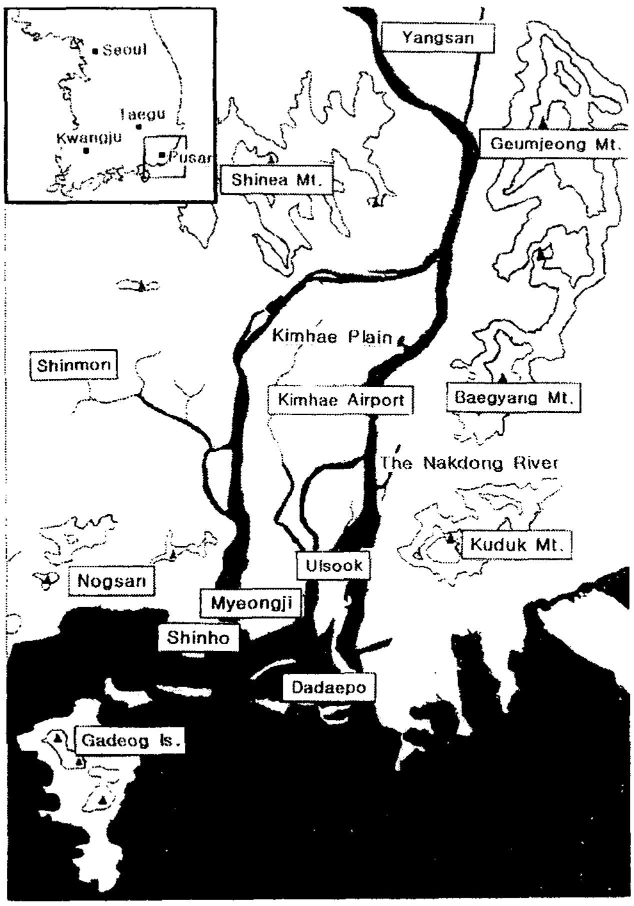


Fig. 1 The Nakdong river mouth and its vicinity

Shown in Fig. 2 are soil profiles crossing a section of north-south direction of the Dadaepo area, which covers 7km along the river mouth (Hyundae, 1973). As it can be seen from this figure, the whole depth of deposits is approximately 70m. Gravel was deposited at first on the bedrock, and then sand, silty clay, finally sand again. However, the thickness of each layer is variable. It was known from the exploration that weak soil deposits are so thick that long piles or deep wells would be required to support heavy structures of the proposed steel mill. Conclusively, the project was abandoned because of the huge foundation cost, but this exploration disclosed important information about the deposits of the river mouth.

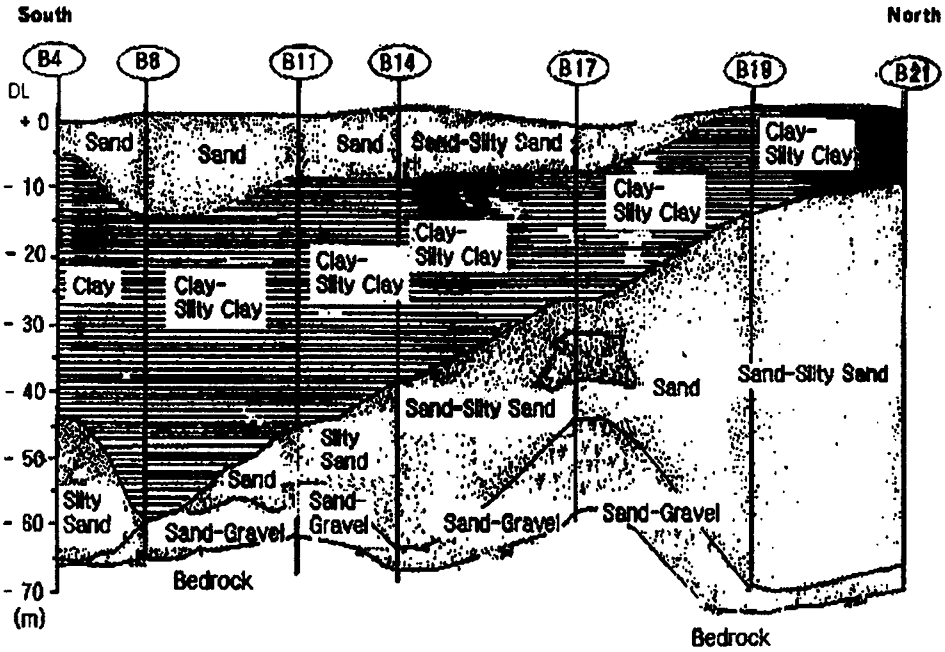


Fig. 2 Soil profile of north-south direction at Dadaepo area

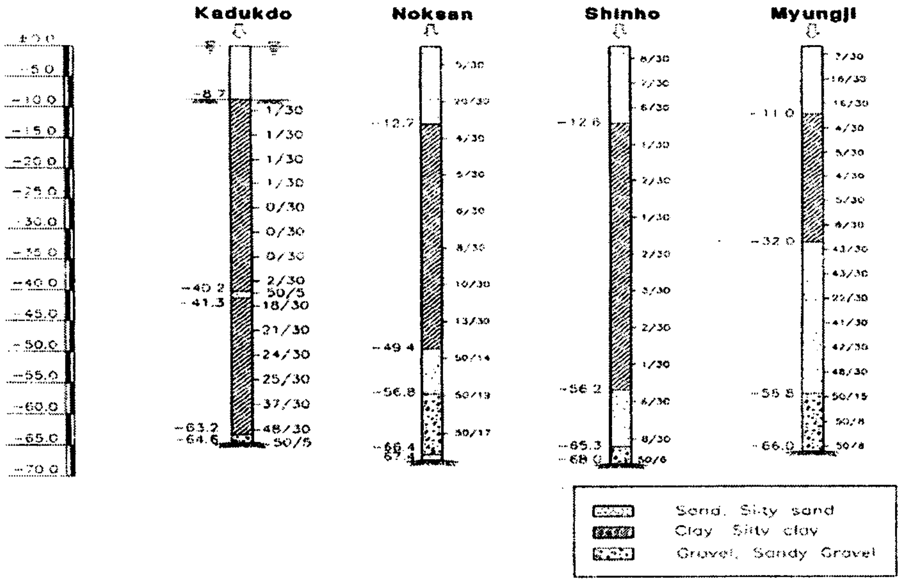


Fig. 3 Soil profiles along the Nakdong River mouth

The subsurface information for the other parts of the river mouth was recently disclosed for the development of new industrial complexes. Fig. 3 shows typical soil profiles of Myungji, Shinho, Noksan, and Kaduk-do areas, all of which are located at the coastline, as shown in Fig. 1. The whole thickness of soil deposits is not much different from each other. It is noticed that there is no upper sand layer at Kaduk-do because this is an offshore soil profile. The upper sand layer forming the land surface is a recent alluvial deposit caused by frequent flooding.

The deposits of the Kimhae plain and the Nakdong river mouth are unusually thick compared to those of the other coasts in the Korean peninsula. The possible reasons for that can be explained with the help of geology as follows.

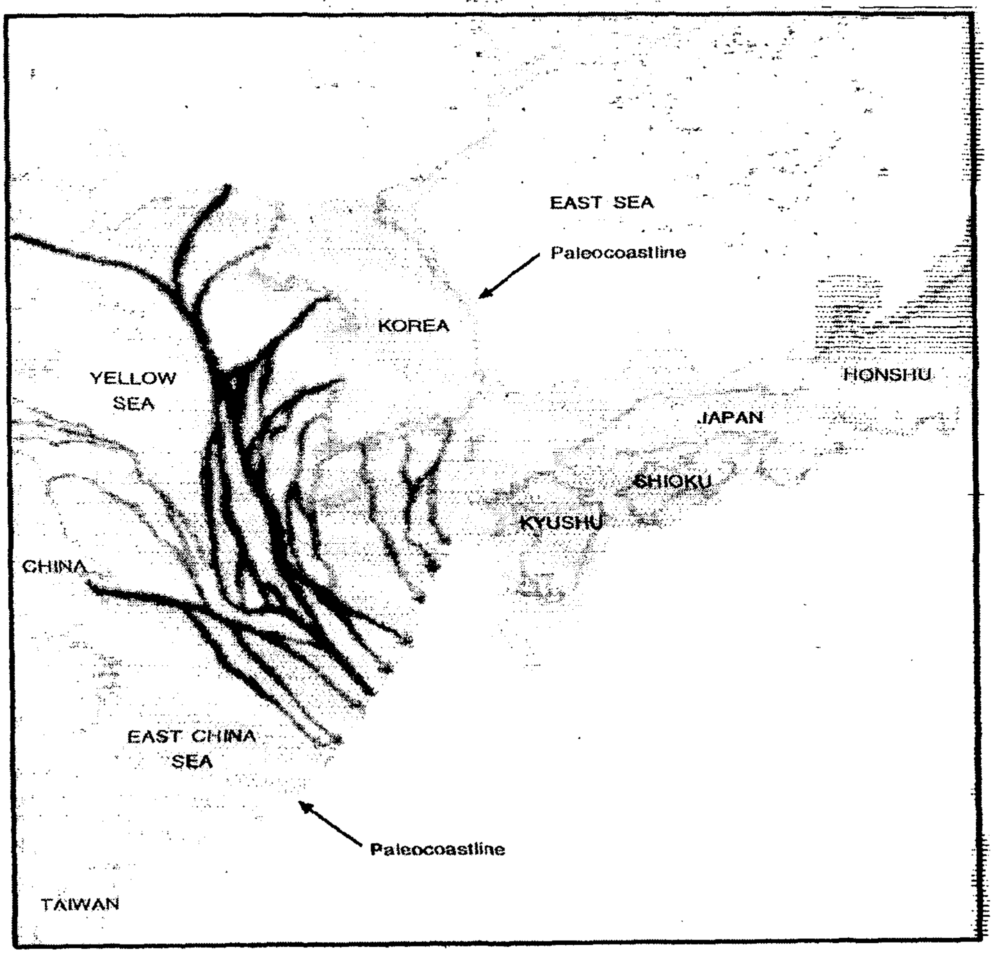


Fig. 4 Paleo-coast line during the glacial age (Park, 1988)

(1) As shown in Fig. 4, the Paleo-coastline during the glacial age (before the Flandlian aggression) extended far to the west of Kyushu. As can be seen in this figure, the coastline during the glacial age was a line extending to the west of Kyushu through Taiwan. Therefore, the present Nakdong River mouth would be a middle part of the old river and would have formed an erosion valley. And coarse materials were deposited on the riverbed in this period.

(2) The second reason is that the present Kimhae plain was a basin in the past, geologically called the Kyungsang Basin (Jung, 1979).

(3) It was estimated that approximately 5m of tectonic subsidence occurred during last 5,000 years (Jung, 1979). But it is unknown whether the subsidence occurred even before 5,000 years.

Table 1 Comparison of thickness of different clay deposition at various locations

| Location | Thickness(m) | Natural Water Contents | Liquid Limit | References |
|---|---|---|---|---|
| Kansai airport | 20(alluvium)<br>160(diluvial clay) | 30~140<br>25~90 | 30~115<br>30~150 | K.I.A.C.(1993) |
| Bangkok clay | 16(soft clay)<br>12(stiff clay) | 133±5<br>40~50 | 123±2<br>20 | Bala et al.(1985) |
| San francisco bay mud | 16.5~17.4 | 90 | 88 | Bonapard & Mitchel(1979) |
| Muar marine clay, Malaysia | 19.9 | 60~110 | 60~120 | Brand & Premchit(1989) |
| Changi, Singapore | 12(upper marine clay)<br>14(lower marine clay) | -<br>- | 85±9<br>78±7 | Bala et al.(1985)<br>Bala et al.(1985) |
| Banjamarsin clay, Indonesia | 32 | 75~100 | 78~108 | Subagio(1991) |
| Kimhae, Dadaepo | 10.0~45.0 | 35~50 | 32~53 | This paper |
| Kimhae, Noksan | *43.9(ave.) | 30~70 | 30~65 | |
| Kimhae, Myungji | **29.8(ave.) | 45~80 | 55~90 | |
| Kimhae, Yangsan | 24.0~33.3 | 26.0~60.0 | 25.0~60.0 | |

* included the upper loose sand layer of 7.1m

** included the upper loose layer of 10.3m

In addition to depositional environments of the Nakdong River mouth, one of the major concerns of geotechnical engineers is the engineering behavior of the soft silty clay. Table 1 shows a comparison of thickness of different clay deposition at various locations throughout the world. The thickness of Kimhae clay is variable but the layer at the Noksan area is 44m thick in average, the maximum thickness of which is 60m. On the other hand, most clays are approximately 20m or below in thickness. Only Banjamarsin clay in Indonesia and Western Johore clay in Malaysia are 32m and 35m in thickness respectively. Although the whole depth of Kansai clay is 180m including diluvial clay, alluvium is only 20m. There is no evidence that Kimhae clay is diluvium. Conclusively, we can see from this comparison that the layer of Kimhae clay is unusually thick.

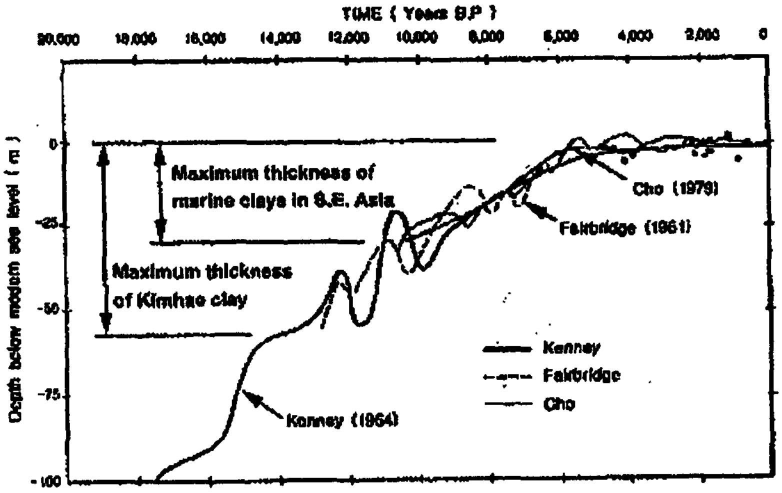


Fig. 5 Sea level rise during Flandrain aggression

It is well known that the marine clay has been deposited with the rise of sea level. Different researchers show that the rise of sea level with time throughout the world is almost similar. The maximum thickness of Kimhae clay is plotted on Fig. 5 together with that of the marine clay in Southeast Asia. And it is known that Kimhae clay has been deposited from approximately 15,000 years before present. However, it is likely that the clay is much younger than the age estimated from this curve, because clay particles would have settled down much later than the sea level rise.

Table 2 Measurement of radio carbon dating for Kimhae clay at Kaduk-do

| Elevation(from S.L.) | -12.0M | -32.0M | -44M |
|---|---|---|---|
| Age(years B.P.) | 6,184±68 | 10,418±61 | 11,741±74 |
| $\delta^{14}C()$ | -537.5±3.8 | -728.2±2.0 | -769.5±2.1 |
| $\Delta^{14}C()$ | -539.6±3.9 | -728.2±2.1 | -769.5±2.1 |
| Percent modern | 46.04±.39 | 27.18±2.1 | 23.05±.21 |

In order to disclose the age of sedimentation of the clay deposit, the radio carbon dating was conducted with the clay samples taken in the coast of Kaduk-do. Table 2 shows the result of the measurements for the clay deposit. It was known from the measurement that the clay deposited at 44m below mean sea level was approximately 12,000 years old. With the values measured at different depth, a variation of the sedimentation rate with time for Kimhae clay can be established. It was known that the sedimentation rate was 9.1mm/year between 12,000 and 10,000 years before present, but decreased at the rate of 1.9 to 2.3mm/year.

Table 3 Comparison of the rate of sedimentation of Kimhae clay with other clay located across the world

| Type of Deposit | Place | Rate of Sedimintation (cm/1,000yr) | Reference |
|---|---|---|---|
| Marine | Goldthwait sea, Canada | 1,200~1,600 | Locat and Lefgebvre(1983) |
| | Oslofjord, Norway | 80~250 | Richards(1976) |
| | Baltic, Sea | 30 | Kukal(1971) |
| | | 30~100 | Schearer(1972) |
| Coastal | Gulf of Marine, USA | 90~180 | Locat and Lefgebvre(1983) |
| | San Francisco Bay, USA | 30~130 | Olsen(1978) |
| | Avonmouth, UK | 250- | Skempton(1970) |
| | Pisa, Italy | 250 | Skempton(1970) |
| | Chao Phraya, Thailand | 200~300 | Kukal(1971) |
| | West Coast, Malaysia | 10 | Cox(1972) |
| | North Coast, Borneo | 90 | Cox(1972) |
| | Indonesia | 120~300 | Cox(1972) |
| | **Kimhae clay, Korea** | **210~910** | **This Paper** |
| Deltaic | Mississippi, USA | 12,000 | Cox(1972) |
| | Fraser, Australia | 5,000~30,000 | McClelland(1967) |
| | Rhone, France | 1,700 | Kukal(1971) |
| | Chao, Phraya, Thailand | 2,500~30,000 | Skempton(1970) |

Table 3 shows a comparison of the rate of sedimentation of Kimhae clay together with other clays located across the world. Generally speaking, the sedimentation rate of Kimhae clay was faster than other coastal clays, but much slower than other deltaic clays such as Mississippi, Frase, Rhine, and Chao Phraya.

## ENGINEERING PROPERTIES OF KIMHAE CLAY

Since the clay deposit is unusually thick, there may be suspicious whether or not the whole depth of the clay is of a marine origin. It is because the lower depth may be of a lacustrine origin. According to Zonneveld (1963), a marine deposit may possess more than 3% of potassium because of its depositional characteristics. A study revealed that the clay exhibited 1.5mm/l of potassium ion at 42 m below mean sea level, which is equivalent to 10% of potassium content. Therefore, there was no evidence of a lacustrine origin

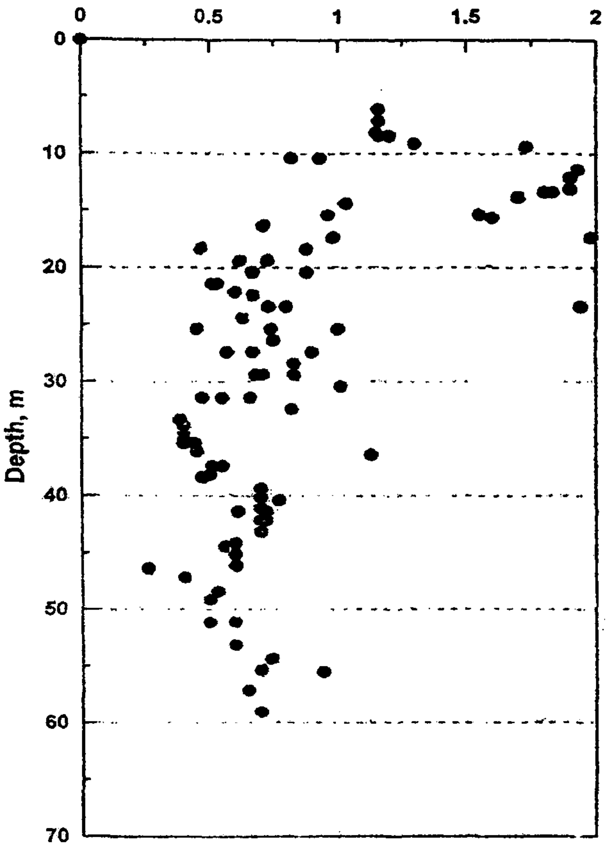


Fig. 6 Variation of over-consolidation ratio with the increase of clay depth at Noksan industrial site

Fig. 6 shows variations of over-consolidation ratio (OCR) with the increase of clay depth at the Noksan site. The upper part of the clay layer shows over-consolidated behavior, but the OCRs at the lower part is lower than unity. This trend was the same at other locations in the deltaic area. The under-consoilidated behavior of Kimhae clay shown in this figure may be caused by soil disturbance of samples tested, accompanied by sampling and testing. This may be true because more sophisticated sampling techniques are required in Korean practice in order to get the best quality samples. Another possibility of showing lower OCR may be caused by the difference of procedures estimating the maximum past pressure. In order to evaluate the maximum past pressure in more accurate ways, various techniques can be used such as:

(1) Drawing of consolidation curves by different presentation, based on the results of consolidation test with load increment ratio of one or less

(2) Constant rate strain test

(3) Field test

Average OCRs determined using above methods were increased in general but OCRs were still below unity at the lower part of the clay layer.

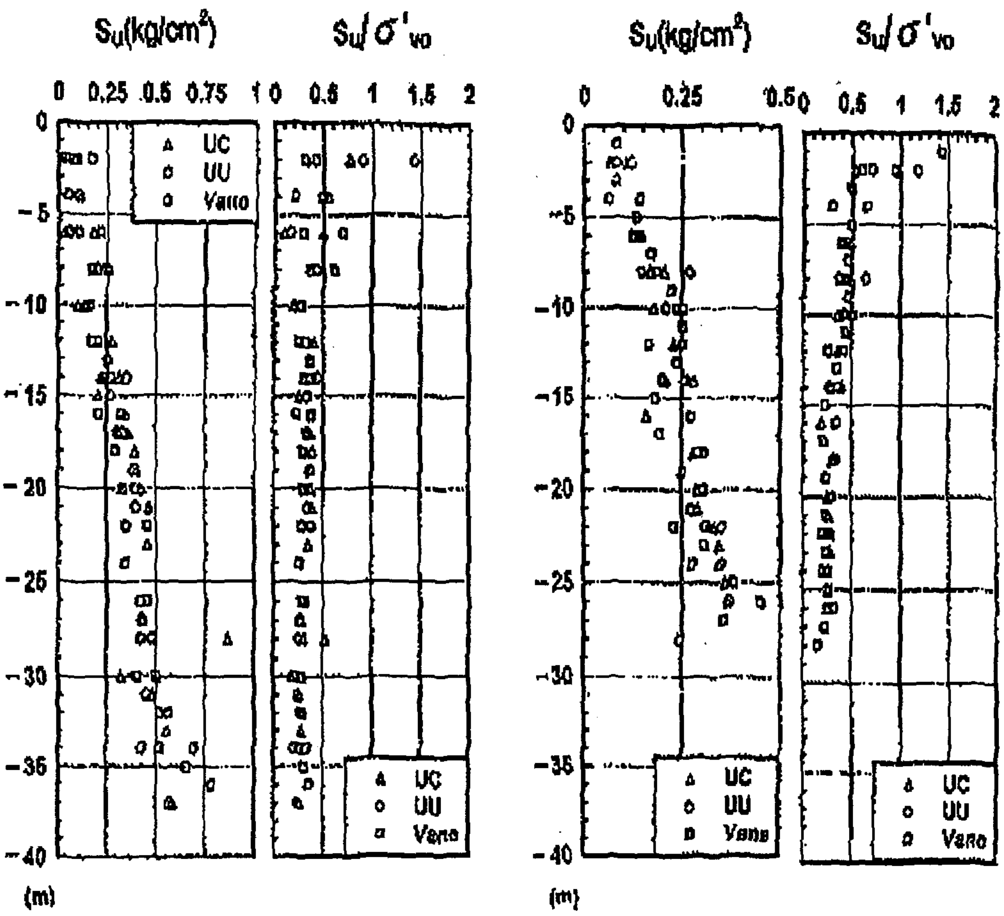


Fig. 7 Variation of undrained shear strength and strength increase ratio with the increase of depth

Fig. 7 shows variation of undrained shear strength and strength increase ratio with the increase of soil depth for the Kaduk-do breakwater site. It was revealed that undrained shear strength did not increase linearly with the increase of depth, as can be seen in normally consolidated clay, and strength increment ratio decreased with depth as well. Even at deep depth, the undrained shear strength of Kimhae clay was rare to exceed $0.5kg/cm^2$. Strength increase ratio at lower part of the clay layer decreased up to 0.2.

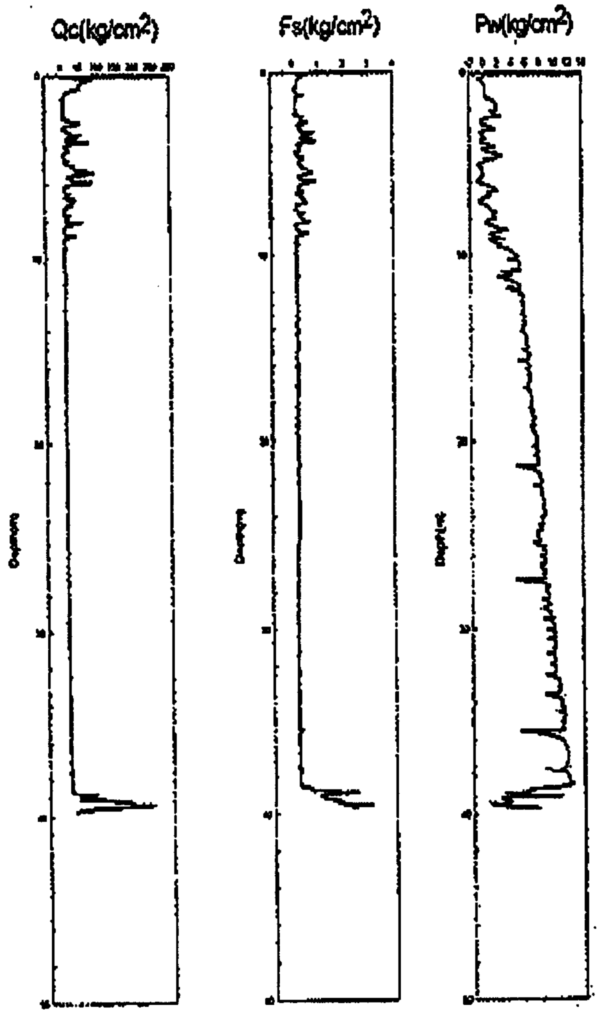


Fig. 8 Results of piezocone test for a borehole of Noksan site.

Also shown in Fig. 8 are results of a piezocone test for a borehole of the Noksan site. It was known that tip resistance $q_c$ in the clay layer slightly increased with depth but the increase rate was not as great as that can be seen in typical normally consolidated clay

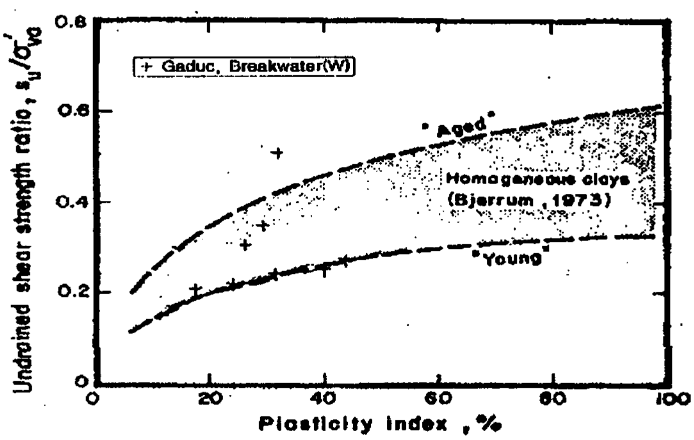


Fig. 9 Relationship between undrained shear strength ratio and plasticity index for the Kaduk breakwater site.

Shown in Fig. 9 is the relationship between undrained shear strength ratio and plasticity index for the Kaduk breakwater site. It was known from the figure that many plots are lied on the line of young normally consolidated clay that was suggested by Bjerrum (1972).

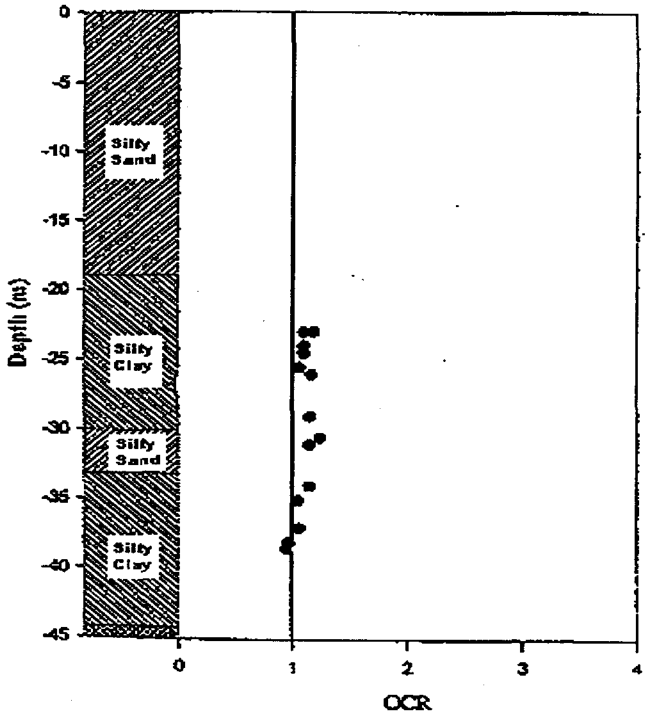


Fig. 10 Determination of over-consolidation ratio by means of field test (Chung, 1999)

Chung (1999) measured the development and dissipation of excess pore water pressure and settlement during the application of surcharge at the Ulsook-do site. This project was performed to preload for the floating foundation of a three-story building. The maximum past pressure could be determined by measuring the variation of pore water pressure together with the application of surcharge load. It was known from the figure that the OCR was only slightly lower than unity at the elevation of 30m below ground level.

From the detailed examination from lab consolidation tests, shear strength behavior, and field settlement tests for Kimhae clay, it could be concluded that Kimhae clay does not exhibit the engineering behavior of typical normally consolidated clay. The clay showed under-consolidated behavior from lab tests, while it could be classified into to young normally consolidated clay from field tests.

## PREDICTION AND MEASUREMENT OF SETTLEMENTS DURING RECLAMATION

Since the existing ground level near the coastline is almost consistent with sea level, at least 4m of filling on the existing ground are necessary to form new ground level for the industrial complexes. The filling works were performed after installing vertical drains to accelerate the consolidation settlement. Large consolidation settlements occurred during filling on the soft ground.

Table 4 Comparison of prediction and measurements of consolidation settlements (Chung, 1999)

| Sites | Average Thickness(m) | Average Fill Height(m) | Predicted Settlement(cm) | Measured Settlement(cm) | Remarks |
|---|---|---|---|---|---|
| Myungji | 19.5 (15.2~21.2) | 5.4 | 106.0 | 171.1 | Treated with vertical drain |
| | | 6.5 (5.0~10.0) | 106.0 | 87.9 (62.2~97.9) | No treatment |
| | | 5.9 (5.0~8.7) | 116.0 | 148.2 (82.2~240.9) | Treated with vertical drain |
| Shinho | 26.2 (21.0~33.5) | 3.6 (2.9~4.6) | 79.7 (45.2~124.6) | 228.5 (172.6~318.2) | Ditto |
| Noksan | 36.8 (1.4~59.8) | 5.5 (4.3~10.5) | 132.8 (0.7~2.2) | 251.4 (0.9~4.5) | Ditto |
| Shinho approach road | 38.7 (26.5~50.8) | 4.8 (4.0~6.2) | 170.3 (134.8~203.7) | 210.3 (148.6~251.9) | Ditto |
| Yangsan | 26.7 (22.2~34.0) | 5.0 | 218.5 | 389.5 | Ditto |

Table 4 shows a comparison of predicted and measured settlements at different locations. It can be noted that measured settlements are 1.5 to 3 times more than predicted. For example, the actual settlement was 4.5m for 10.5m-fill height but prediction was only 2.2m. This gives a lot of difficulties to the land owner because of an additional reclamation budget. Also from a viewpoint of engineering, more than 1.5 times difference between prediction and measurement gives a serious problem to designers.

## DISCUSSION

Presented in Table 5 is engineering properties of Kimhae clay together with those of some other clays for comparison of their properties. From the comparison it is known that the compression ratio of Kimhae clay is considerably low compared with Nong Ngu Hao clay and Muar clay that are typical normally consolidated clays. Low compression ratio gives low consolidation settlement, as can be seen from Terzaghis consolidation theory. Now it is necessary to evaluate components of compression ratio.

Table 5 Comparison of compression ratio for different clays

| Clay | Ave. Clay thickness(m) | Ave. WC (%) | Ave. LL (%) | Ave. PI | Void Ratio | Comp. Index | Ave. Comp. Ratio |
|---|---|---|---|---|---|---|---|
| Noksan | 40 | 55.0 | 55.0 | 24.7 | 1.3 | 0.75 | 0.27 |
| Myungji | 19.5 | 52.6 | 52.6 | 29.5 | 1.54 | 0.6 | 0.24 |
| Yangsan | 25 | 70.0 | 65.0 | 27.5 | 1.5 | 0.65 | 0.29 |
| Ulsuk-do | 26 | 47.0 | 38.4 | 23.8 | 1.53 | 0.54 | 0.21 |
| Nong Ngu Hao | 15.0 | 80.0 (50~110) | 90.0 (75~105) | 37.5 (30~45) | 2.5 (2.0~3.0) | 1.5 (0.6~2.4) | 0.42 |
| Muar | 16 | 92.5 (60~125) | 75.0 (60~90) | 35.0 (25~45) | 2.2 (1.4~3.0) | 1.35 (0.6~2.1) | 0.42 |

Compression ratio is defined as $C_c/(1+e)$. If compression index $C_c$ is underestimated, the compression ratio becomes low. Since low $C_c$ may come from soil disturbance, it can be corrected using Schmatermanns method or others. Chung (1999) has made the correction but there were still a big gap between the estimated and measured settlements. According to empirical formula (Terzaghi and Peck, 1967),

$$C_c=0.009(LL - 10) \qquad (1)$$

for normally consolidated clay. Since estimated compression index is 0.45 for 60% of liquid limit from the above equation, the averaged measured values of 0.75 and 0.65 for the Noksan and Yangsan sites are much higher than those estimated. Conclusively, measured compression index is not likely to affect low estimation of the settlement.

When void ratio is overestimated, this would result lower compression ratio. However, there is no possibility of overestimation of void ratio because void ratio becomes less if soil disturbance occurs. Therefore, the initial void ratio measured is considered to be reasonable. If this is true, it may be concluded that the value is larger than that of typical normally consolidated clay. In other words, the deposits of Kimhae clay have not yet reached the state of normally consolidated state. This does not mean that excess pore water pressure exists over whole depth of the clay layer, but means that it may exist only at a thin layer in its middle part. Even though there exists excess pore water pressure in a certain layer, its amount would be so negligible that it would be difficult to detect by a piezometer

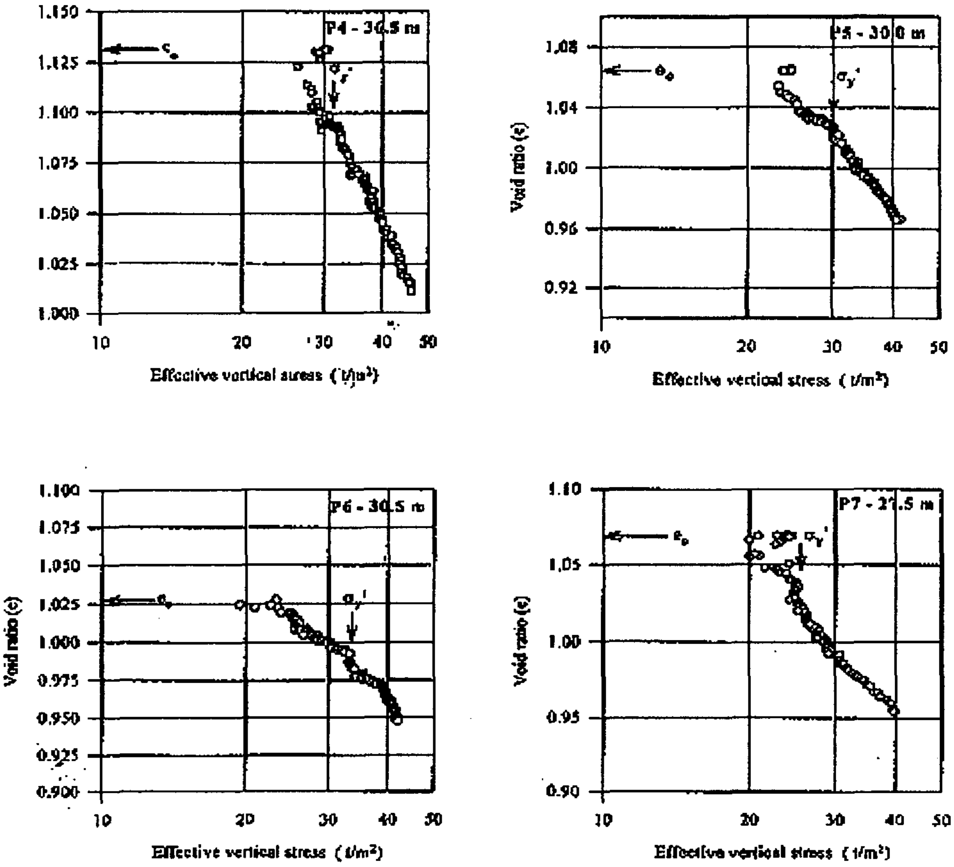


Fig. 11 Relationship between effective stress and settlement measured in-situ (Chung, 1999)

Large void ratio may be due to the reason that the clay has had not experienced enough aging after sedimentation. For young sedimented soils, void ratio becomes smaller as aging proceeds, as indicated by Bjerrum (1972).

Shown in Fig. 11 is the relationship between effective stress and void ratio measured in-situ for the clay layer at Ulsuk-do (Chung, 1999), which was obtained by measuring excess pore pressure and settlements during the application of surcharge. Through the measurements, maximum past pressure could be predicted as shown in the figure. It is noted that the settlement that occurred prior to reach maximum past pressure is unusually large. This may be due to soil disturbance that was caused by the smear zone formed when vertical band drains were installed. The initial settlements of the upper loose sand layer could have also contributed to the occurrence of unusual large settlement of the soft ground.

Table 6 Measured artesian pressures at different locations

| Location | Borehole No. | Elevation measured below GL(m) | Measured artesian head (m) | References |
|---|---|---|---|---|
| Yangsan | SPW-A05 | 24.70 | 2.65(2.80*) | KGS(1990) |
| | SPW-A09 | 26.80 | 2.74(2.50) | |
| | SPW-A17 | 28.50 | 1.89(1.30) | |
| Kaduk-do | NB-2 | 45.39 | 1.36 | Pusan Harbour(1998) |
| | | 27.21 | 1.54 | |
| | NB-77 | 40.3 | 1.57 | |
| | | 26.5 | 1.35 | |
| Boat race site | BH-3 | 33.0 | 1.38 | Daewoo Eng. (1999) |
| | BH-4 | 34.5 | 1.58 | |
| | BH-5 | 48.0 | 0.50 | |

* measured with piezocone

When a clay layer is subjected to an artesian pressure and the pressure is released by drainage such as vertical drain installations, large settlement may take place by the pressure release. From site exploration for several sites, artesian pressure head of up to 3m was detected. Table 6 shows the measured artesian pressures at different locations within the Nakdong delta area. Up to now, it was confirmed that the pressure appeared at three sites as shown in the Table. The pressure exists at the underlying sand layer of 25m to 50m below ground level. Since the Kimhae plain was surrounded by mountains of approximately 200m to 800m in height, the source of the pressure may be high water table within the mountains.

## CONCLUSIONS

The Nakdong River Mouth has been a focus for the industrial development of the Korean Government since the early 1990s. Important residential complexes and a new port will be located in the area. During reclamation works for the development of industrial complexes, unusual large settlements have been occurred. The under-estimated settlement may be caused by the incorrect estimation of soil parameters arising from soil disturbance. However, it seems that there are other possible reasons coming from unique depositional features of the Nakdong River mouth.

According to laboratory tests, Kimhae clay may be classified into under-consolidated clay, although a field test shows normally consolidated behavior. A radioactive dating shows that sedimentation rates are relatively large compared to coastal clays of the world. Young deposition may give unusual large settlement. The examination of compression ratio of Kimhae clay gives low one compared to other normally consolidated clays. If the smaller ratio is caused by higher void ratio coming from young deposition of Kimhae clay, this may be an explanation of large settlement.

Artesian pressure was detected at several sites in the Kimhae plain. The release of the artesian pressure by installation of vertical drains may cause additional consolidation settlements. Reclamation works have been performed after installing vertical drains in order to accelerate the settlements.

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