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# Effect of permeability and stiffness of treated column on consolidation phenomenon of improved ground

## Effet de la perméabilité et de la rigidité de la colonne traitée dans le phénomène de tassement du terrain amélioré

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ABSTRACT
When a group column type improved ground consisted of treated clay columns and soft clay is subjected to overburden pressure, the ground settlement takes place much faster than that of unimproved ground. This phenomenon is considered due to high permeability of treated column in Nordic countries. In Japan, on the other hand, it is considered due to high compressibility of treated column. In this study, the permeability of treated clays and the consolidation phenomenon of the improved ground were investigated by a series of element oedometer tests and permeability tests, and model consolidation tests and numerical analyses, and by analyzing long time follow-up observations from site. It was found that the permeability coefficient of cement treated clays decreased slightly with increasing the amount of cement, while this phenomenon was not confirmed in lime treated. Based on the investigations on consolidation of the improved ground, it was found that the consolidation phenomenon was much influenced by not only the permeability but also the compressibility of the treated column. This study revealed that the consolidation of the column type improved ground with high compressibility of column proceeded faster that that of unimproved ground even if the permeability of the column is lower than that of the untreated clay.

RÉSUMÉ
Bien que l'application d'une charge sur le terrain amélioré selon la méthode du malaxage profond permette de tasser le sol composé d'argile traitée et d'argile plastique non traitée, la vitesse de tassement d'un terrain amélioré est généralement supérieure à celle d'un terrain non amélioré. Actuellement, la raison de cette supériorité n'est pas connue. Dans cette étude, la perméabilité de l'argile traitée a été mesurée au laboratoire avec des essais de tassement et des essais de perméabilité. Aussi les observations longes au terrain ont été employées. Ensuite, des études de tassement sur modèles et des analyses numériques ont été réalisées afin d'étudier le phénomène de tassement du terrain amélioré. Le rapport mesuré entre l'indice de perméabilité et l'indice de vides est légèrement inférieur lorsque la quantité de ciment est augmentée, bien que les argiles traitées à la chaux n'aient pas confirmé ce phénomène. Les analyses de tassement du terrain amélioré indiquent une déformation par cisaillement de l'argile traitée et un tassement de l'argile non traitée. Ainsi, on peut en conclure que la vitesse de tassement du terrain améliorée est due principalement à la forte rigidité de l'argile traitée.

## 1 INTRODUCTION

The Deep Mixing Method (DMM) is one of soil stabilization techniques for soft cohesive soil, where soft soil is stabilized by mixing binder such as cement or lime. The DMM has been developed in Nordic countries and Japan, and has been frequently applied in many countries. The most benefit of the technique is high strength of treated soil being obtained in a short period. The group column type improved ground, a sort of composite ground consisted of treated columns and clay, is often applied to light weight structures such as embankment or dike in order to reduce ground settlement and to improve stability. The consolidation settlement of the group column type improved ground takes place much faster than that of the untreated ground in general. Nordic countries and Japan have quite different views on the cause of the phenomenon (Broms and Boman, 1977)(Terashi and Tanaka, 1983) and do not reach the conclusion: due to the high permeability of the treated column in Nordic countries, but due to the high compressibility of the treated column in Japan. It is considered that this is probably due to the difference of properties of clays and binders in these countries.

According to many researches on the vertical drain method, the consolidation process of the improved ground is influenced by many factors including the permeability and the compressibility of the treated column. However, little research has been conducted on the consolidation phenomenon by the combined effect of the permeability and compressibility of the treated column. The aim of this study is to investigate the consolidation of the group column type improved ground especially by focusing on the combined effect of the permeability and compressibility of treated column. In the study, the permeability and compressibility characteristics of treated clay were investigated on three types of treated clays excavated in Finland and Japan first. The laboratory model tests and numerical analyses were conducted in order to investigate the consolidation phenomenon of the group column type improved ground. In this text, the effect of the permeability and compressibility of treated column on the consolidation phenomenon are briefly discussed as well as the test procedures. Some site results are also given.

## 2 PERMEABILITY PROPERTIES OF TREATED COLUMN

### 2.1 *Clay samples and procedures of laboratory test*

In this study, three types of clay were used for the permeability and oedometer tests: Arabianranta and Fallkulla clays excavated in Finland, and Kawasaki clay in Japan. The physical properties of these clays are shown in Table 1.

Table 1:Physical properties of clays

| | | Arabianranta clay | Fallkulla clay | Kawasaki clay |
|---|---|---|---|---|
| Density of soil particle | | 2.736g/cm$^3$ | 2.765g/cm$^3$ | 2.692g/cm$^3$ |
| Liquid limit | | 158.0% | 67.0% | 64.8% |
| Plastic limit | | 24.0% | 23.2% | 25.2% |
| Plasticity index | | 134.0 | 43.8 | 39.6 |
| Organic matter content | | 8.21% | 0.86% | 2.65% |
| Soil particle | 0.075~2 mm | 2% | 2% | 9% |
| | 0.005~0.075 mm | 14% | 13% | 49% |
| | ~0.005 mm | 84% | 85% | 42% |

Arabianranta clay is a humic soil and characterized by a relatively high liquid limit and a high organic matter content of 8.21%. Arabianranta and Fallkulla clays contain a greater proportion of fine-grained particle than Kawasaki clay. Kawasaki clay contains large amount of silt and is classified as 'silty clay'. In order to simulate the actual construction in the two countries, Normal Portland cement and quicklime produced in Finland were used to the Finnish clays, while Japanese ones were used to the Japanese clay.

The test specimens of treated clay were manufactured according to Japanese Standards (2000a) as follows. The clay and some amount of water were mixed throughout about one hour in a vacuum mixer for ease of manufacture of uniform treated clay specimens. Then either cement or lime was mixed with the clay slurry about 10 min. Amount of the binder was changed as 4, 6, 10 and 15% of the binder factor $a_w$, which was defined by the ratio of dry weight of cement to dry weight of soil. The treated clay slurry was poured into either the plastic molds of 5 cm in diameter and 10 cm in height for the permeability tests and unconfined compression tests or the specimen rings of 6 cm in diameter and 2 cm in height for the oedometer tests.

After curing them at a constant temperature of 20° in Celsius for 28 days, the oedometer and permeability tests were carried out. The oedometer test was conducted according to the Japanese Standard (2000b) in which the vertical pressure was increased step wisely at one-day interval to the maximum pressure of 1254.4 kN/m$^2$. The permeability of treated clay was measured in a triaxial apparatus by the constant head permeability tests after isotropical consolidation with three confining pressures to investigate their effect. The confining pressure in the triaxial apparatus was selected as lower, at and higher than the consolidation yield stress, while the consolidation yield stress was estimated by the unconfined compressive strength on the reference specimen.

## 2.2 *Results of laboratory test*

As the oedometer and permeability tests were already presented in detail (Takahashi and Kitazume, 2004), major test results are briefly discussed in this text.

Figure 1 shows the relationship between the permeability coefficient and the void ratio of three clays measured in the oedometer and permeability tests. In the figure, the oedometer test results measured at the vertical pressure lower than the consolidation yield stress are not plotted because the consolidation process was not precisely detected. The coefficients measured by the two tests were almost coincided. The figures show that the permeability coefficient of all untreated and treated clays increased almost linearly in the logarithmic scale graph with increasing the void ratio irrespective of clay and binder. A similar phenomenon has been reported previously on untreated clay by Tavenas *et al*. (1983). As shown in Fig. 1(a) for Arabianranta clay, the measured coefficients were almost coincided and increased with increasing the void ratio irrespective of the amount of binder. For Fallkulla clay shown in Fig. 1(b), the permeability coefficient increased with the void ratio. However, it is found that the coefficient became low with increasing the amount of binder. It is of interest in Fig. 1(b) that the permeability coefficient of the lime treated clay was comparatively high rather than that of the cement treated clays, but almost same order as the untreated clay. It is clearly found in Fig. 1(c), for Kawasaki clay, that the permeability became low with increasing the amount of cement. The permeability coefficient of the lime treated Kawasaki clay was also higher than that of the cement treated clay, but almost same order as the untreated clay.

These data show that the permeability of treated clay is influenced not only by the void ratio of treated clay but also the type of binder. The different effect of binder type on the permeability might be due to that the space of soil particle is filled by the cement hydrate in the cement treated clay but not in the lime treated clay. Further research is necessitated. In the test conditions of this study, the permeability of lime treated clay is not much higher but almost the same order of that of untreated clay. The chained lines in Fig. 1(c) are approximated relations for evaluating the laboratory model consolidation test results and estimating the parameters in numerical analyses.

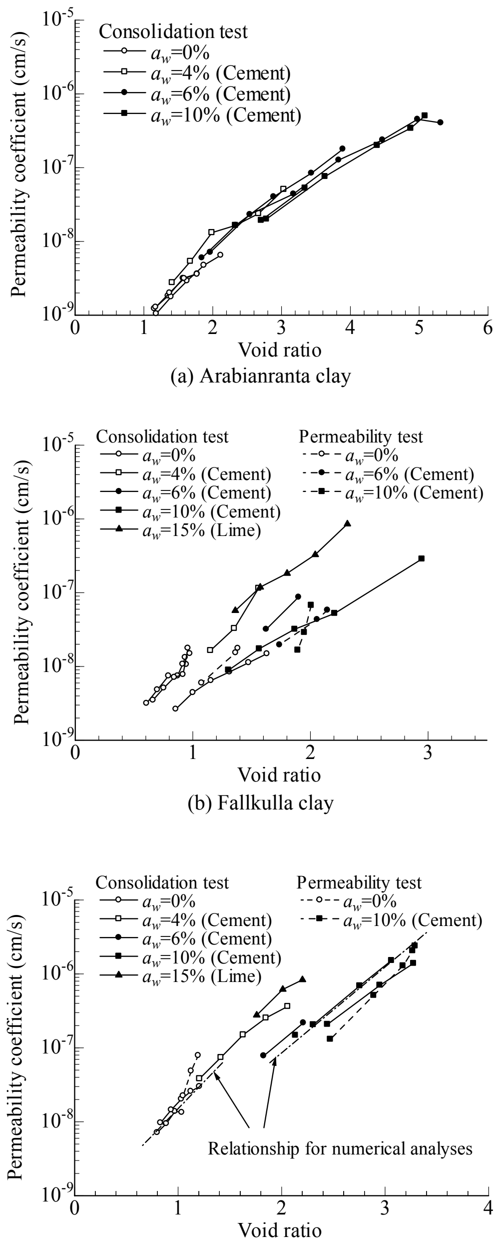


Figure 1. Relationship between permeability coefficient and void ratio

## 3 PROCEDURES OF MODEL TEST AND NUMERICAL ANALYSIS

### 3.1 *Procedures of laboratory model consolidation test*

To investigate the consolidation characteristics of the column type improved ground, a series of laboratory model consolidation tests was carried out on the improved ground with a single treated column. According to the element test results, Kawasaki clay and Kawasaki treated clay were selected as the model ground to carry out several tests within the limited period. The results of the model tests can be applicable to the other clays, because the basic characteristics on the permeability of treated clays are almost same irrespective of the type of clay and binder as described in the previous section.

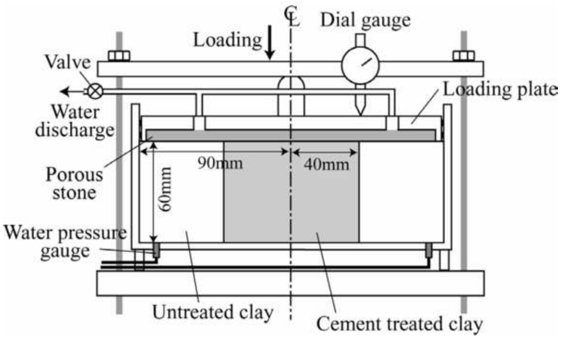


Figure 2. Schematic view of consolidation model test

The column improved model ground is schematically shown in Fig. 2, in which the clay of 18 cm in diameter and 6 cm in height is improved by the treated column with 4 cm in diameter corresponding the replacement area ratio $a_s$ of 19.8%. The model ground was subjected to vertical pressure through the steel loading plate. The loading plate was precisely lathed to the inner diameter of the specimen box in order to assure sufficient watertight at its periphery. As the bottom of the box was impermeable, water in the model ground was allowed to flow out only through the porous stone embedded in the plate.

The model ground was prepared as similar manner as the element test specimen as follows. Kawasaki clay and some amount of water were mixed throughout about one hour in a vacuum mixer to manufacture uniform clay slurry. The clay slurry was poured into a container with the same diameter of the specimen box and pre-consolidated at the vertical pressure of 11.3 kN/m$^2$. After confirming the completion of pre-consolidation, the central part of the model ground was excavated to make a cylindrical hollow of 4 cm in diameter for cement treatment. The excavated clay was mixed with Normal Portland cement powder of $a_w$=10%, and the treated clay mixture was carefully poured into the hollow by a help of vibration not to entrap air bubble in the treated clay. The model ground was cured at a constant temperature of 20° in Celsius for 28 days. Then the model ground was removed from the container and set up in the specimen box after trimming its both ends to the height of 6 cm. The drainage pipe and the porous stone fully saturated by de-aired water were set for the consolidation test. In the test, the vertical pressure was increased step wisely to 8.7 and 17.4 kN/m$^2$ per 24-hours' interval. At each loading step, the water drainage was allowed after confirming that the excess pore water pressure measured at the bottom of the model ground was fully developed. During the consolidation, the settlement of the model ground as well as the pore water pressure was measured at an appropriate time interval.

### 3.2 *Procedures of numerical analysis*

Numerical analyses were carried out by the finite element program code 'GeoFem' (Kobayashi, 1984). The 'GeoFem' has been adapted to many construction projects of port and airport facilities in Japan. According to the axial symmetric condition of the model ground, a half part of the ground was simulated in the calculation. The numerical models for untreated and treated clays were a linear elastic model to highlight the effect of the permeability and compressibility of the treated clay. The soil parameters of untreated and treated clay in the calculation are summarized in Table 2, which were estimated by the element test results except the Young's modulus of the treated clay and the Poisson's ratio. The Young's modulus of the treated clay in Table 2 was estimated by a back calculation of the consolidation model test. The Poisson's ratios of untreated and treated clay were assumed as 0.3, which is a commonly accepted value.

Three cases of model tests and two FEM analyses were carried out as summarized in Table 3. In the model tests, the stiffness of the treated clay was changed in the case of EXP1 and EXP2.

Table 2:Soil parameters for numerical analyses

(a) Treated clay

| | $E'$ (kN/m$^2$) | $\nu'$ | $\gamma'$ (kN/m$^3$) | $k$ (cm/s) |
|---|---|---|---|---|
| FEM1 | 7350 | 0.333 | 3.40 | 5.08x10$^{-6}$ |
| FEM2 | 15190 | 0.333 | 4.14 | 6.14x10$^{-7}$ |

(b) Untreated clay

| $E'$ (kN/m$^2$) | $\nu'$ | $\gamma'$ (kN/m$^3$) | $k$ (cm/s) |
|---|---|---|---|
| 560 | 0.333 | 6.70 | 8.50x10$^{-8}$ |

Table 3:List of model tests and numerical analyses

| Test name | Analysis name | Treated clay properties | | |
|---|---|---|---|---|
| | | $a_w$ (%) | $w_0$ (%) | $e_0$ |
| EXP0 (unimproved ground) | | --- | | |
| EXP1 | FEM1 | 10 | 144 | 3.88 |
| EXP2 | FEM2 | 10 | 112 | 3.01 |

## 4 RESULTS OF MODEL TEST AND NUMERICAL ANALYSIS

### 4.1 *Behavior of column improved ground*

The model ground consisted of untreated clay and a treated column takes place one-dimensional deformation as a whole. However, the treated column within the model ground can deform two dimensionally. Figure 3 shows the deformation of improved ground in the case of FEM1 at the loading pressure of 17.4 kN/m$^2$. It can be seen that the middle part of the treated column expanded its diameter and deformed like a barrel, since no horizontal displacement was allowed at the top and bottom ends of the treated column. This is due to that the treated column compensates the high volumetric compressibility of untreated clay.

Figure 4 shows the distribution of vertical and horizontal effective stress induced in the improved ground, which are plotted in the left hand side and the right side of the figure respectively. It is clearly seen that the vertical stress concentrated to the treated column due to the difference in the compressibility of the treated and untreated clays. The horizontal stress induced in the untreated clay remained relatively small value due to small increment of the vertical stress, which allowed the treated clay to expand in diameter to a barrel shaped deformation.

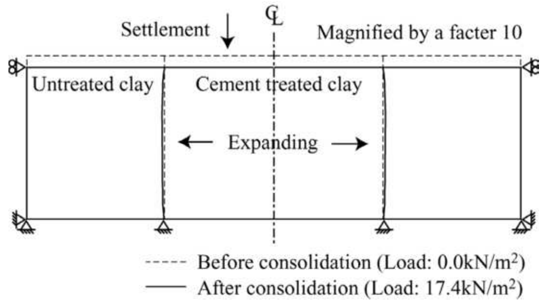


Figure 3. Deformation of improved ground by FEM (Case FEM1)

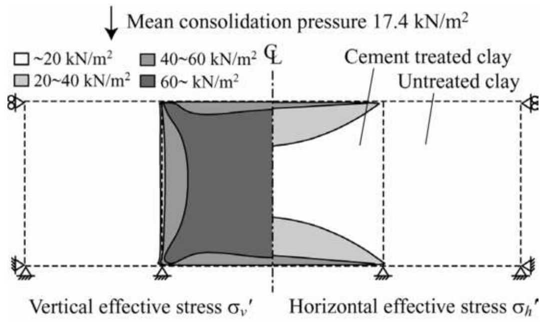


Figure 4. Effective stress of improved ground by FEM (Case FEM1)

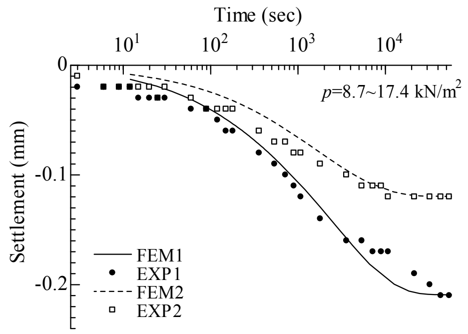


Figure 5. Consolidation settlement curves of improved grounds

Figure 5 shows the consolidation settlement-time curves obtained in the model test and numerical analysis to demonstrate the high applicability of the FEM analysis. In the figure, the model tests data were measured in the two cases at the consolidation pressure of 17.4 kN/m$^2$. As shown in Fig. 5, the settlement curves calculated by the numerical analyses were quite well coincided with the model test data except a little difference at the end of consolidation in the case of FEM1.

### 4.2 *Effect of permeability and compressibility of treated column on consolidation behavior*

It is well known in the vertical drain method that the consolidation process is much influenced by and the permeability and compressibility of drain. This is applicable to the group column type DMM improved ground. In order to these effects on the consolidation behavior, a series of FEM analyses was carried out changing their magnitude. Figure 6 shows the consolidation speed ratio of the improved ground to that of the unimproved ground. In the figure, the permeability coefficient ratio of the treated to the untreated clay is plotted on the horizontal axis, and the compressibility ratio of the treated clay to the untreated clay is plotted on the vertical axis. The point of intersection of unity in both the axes corresponds to the unimproved ground. A series of contour lines indicates the consolidation speed ratio of the improved ground to the unimproved ground.

It is found in Fig. 6 that the consolidation speed of the improved ground became faster when the permeability and/or the compressibility of the treated column increased, especially when both increased. It is of interested that the consolidation speed became about twice in the ground with compressibility ratio of 10 even if the permeability of the treated column was almost the same as that of untreated clay. The experiment data are plotted in the figure together. The data in the case of EXP1 was lower than the calculation, however the data in the case of EXP2 was quite well coincided with the calculation.

The treated column constructed in situ is thought to have similar void ratio to the untreated clay. According to Figure 1 and previous experiences, the permeability ratio of the treated clay is estimated to 0.1 to 0.5 for cement treated clays and to around unity for lime treated clays. The compressibility ratio is estimated to 10 to 100 for cement treated clays and to about 10 for lime treated clays. Based on these estimations, the possible areas for the two types of treated clay are plotted as the circles in Fig. 6. It is found that the consolidation speed becomes about 1.5~20.0 times faster for the cement improved ground and about 1.5~4.5 times faster for the lime improved ground. According to the field test results at Ska-Edeby in Sweden (Broms and Boman, 1977), the settlement-time relation showed that the consolidation speed ratio was about 3.2 times faster for the lime-improved ground. Although the test field was improved by a little different replacement area ratio of 10%, the test result was contained between 1.5 and 4.5 times obtained in this study. Therefore, the high consolidation speed of in-situ improved ground can be explained by the high compressibility.

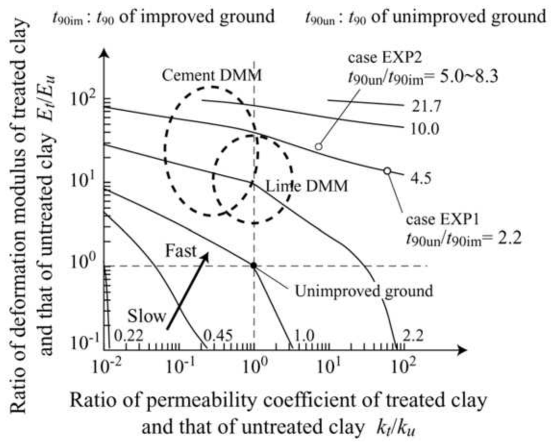


Figure 6. Consolidation speed ratio of the improved ground to that of the unimproved ground

## 5 PERMEABILITY FROM LONG TIME FOLLOW-UP OBSERVATIONS IN HELSINKI

Tali area represents a typical soft soil ground in the western Helsinki. Actual deep mixing contract was carried out at Tali area in 1991.

The area used to be an old industrial and landfill site since 1950. The thickness of surface fill varies from 0.5 to 3.5 meters. Under the fill the thickness of soft clay varies between 3~11 m.

The water content of subgrade clay varies from 50 % to 110 %. The shear strength varies between 10~20 kPa, determined with the vane shear test. Under the clay there is relatively thin silt layer and under that sand and moraine. Water table is at the top of clay layer.

The design criterion for settlements was as much as a 50 years. During this period, the maximum allowed settlement was determined to be 200 mm in street areas and 300 mm in courtyard areas. Without the ground improvement, the maximum settlements could have been more than 1300 mm.

As a part of design, trial deep mixings were conducted (Fig. 7). These trials included different amount of binder and binder mixture (lime-cement ratio).

Figure 7. Typical mixing blade used in deep mixing in Nordic countries

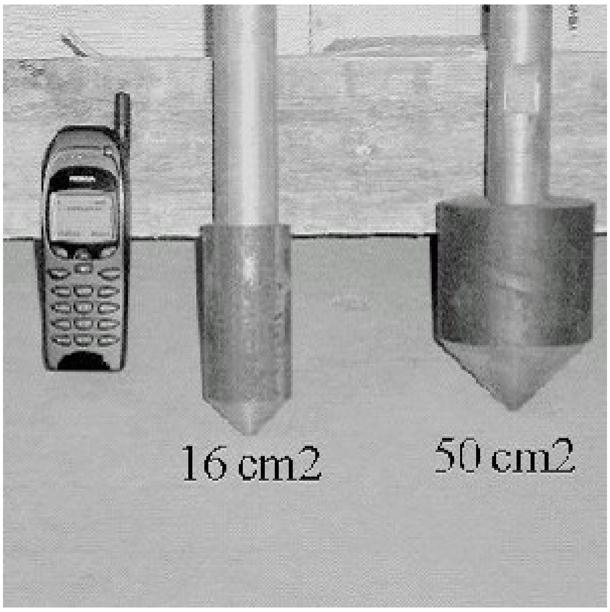


Figure 8. Typical drill heads used in quality control in Helsinki

Trial columns were tested at the age of 30 and 90 days. According to the results, the least variation of shear strength in columns was reached using pure lime binder. Thus, 100 % lime was chosen as deep mixing material. After completion, several quality control operations were accomplished. Field tests were mainly carried out by modified cone penetration test, dynamic probing (Fig. 8-9) and column vane shear test. As the shear strength of untreated clay was 10~20 kPa, the shear strength of treated column quite normally achieved the value > 100 kPa.

During the last decade the shear strength requirements in different contracts has varied between 80~750 kPa and has led to new applications in quality control (Vähäaho 2000).

Long-term observations for settlements have been carried out in the area since 1993. These observations have been analyzed to estimate and predict remaining settlements in street areas (Paatsema and Kangas, 2003). In addition, the settlement parameters for both untreated clay and mixed columns were analyzed. For further analysis, additional field tests, including cone penetration tests, vane shear tests and sampling for both untreated and treated clay were carried out in 2003. Laboratory tests were also included.

Figure 9. Heavy drill rig to use different cone heads

The settlements were calculated with a tangent modulus method using freeware computer application, introduced by Tim Länsivaara 2002. The computer calculations were started with assumption that the ratio of permeability coefficient of the treated clay to that of the untreated clay to be around 40, based partly to what was presented in literature. Though the rate is presented to be even 100 - 1000 in some sources (Broms and Boman, 1978).

Because the above-mentioned ratio could not be fitted to the observations, the field observations were fitted to a mathematical model in order to gain proper estimation for the ratio of permeability coefficient between the treated clay and the untreated clay. The modeled ratio of permeability of lime-treated column and that of untreated clay is presented in Table 4.

Table 4: The modeled ratio of permeability of lime-treated column and that of untreated clay in Tali area in Helsinki

| Observation point (no.) | Ratio of permeability coefficient of lime-treated clay to that of untreated clay |
|---|---|
| 203 | 0.3 |
| 205 | 4.1 |
| 206 | 7.3 |
| 302 | 1.2 |
| 305 | 2.0 |
| 401 | 3.0 |
| 503 | 2.4 |

Also, back calculation with computer application (Länsivaara, 2002) was included. According to back calculation, the ratio is about 5. Although the estimations are quite coarse, it is evident that in Tali case, the permeability coefficient of lime-treated column seems to be rather low. The columns do not seem to function like vertical drains.

Similar results are observed and analyzed in other sites in Finland. The first long-term settlement measurements are from eastern Helsinki (so called Itäkeskus trial area) were also a day nursery was founded with lime column method as all other building were founded by precast concrete piles. The observations were started in 1976 (Vähäaho 1979) and are still ongoing.

Observed settlements give similar value as what was arrived as a result in Tali area for the ratio of permeability coefficient of treated clay to that of untreated clay, and are between 4~6.5.

Pikku-Huopalahti area – built between 1987 and 1991 – is a suburb situated about 5 km northwest from the centre of Helsinki gives some rough information of the rate of settlements on lime-cement treated site (Juntunen and Korhonen, 2002). The thickness of soft clay varies between 13~20 m and water content between 70~150 % of dry weight in the area. In this case, the calculated settlements of untreated clay is in the range of 400~700 mm during 50 years. The observed settlement on treated area is nearby 30 % of the calculated settlement of untreated clay. Typically, the time elapsed for the 50 % consolidation, is around 3~10 years on treated areas. The results show, that at least in this case, there is no vertical drainage inside the cement or lime columns.

The monitoring data from different sites in Helsinki measured during almost three decades show that in order to gain proper estimation for the ratio of permeability coefficient between the lime-treated clay and the untreated clay is from lower than 1 to about 5.

This study recommends the factor 1.0 for the ratio of permeability between lime-treated column and untreated clay. The factor 0.1~0.5 for the ratio of permeability between cement-treated and untreated clays is recommended as well.

## 6 CONCLUSIONS

In this study, the permeability characteristics of cement and lime treated clays were investigated by a series of oedometer and permeability tests, and the consolidation behavior of the column improved ground was investigated by the model tests and FEM analyses. The ratio of the permeability coefficient of treated clay to that of untreated clay was also determined from long time follow-up observations in Helsinki. Major conclusions derived in this study are summarized as follows:

1) The permeability of treated and untreated clays increased exponentially with increasing the void ratio irrespective of the type and amount of binder and the type of clay.
2) The permeability of the cement treated clay became low with increasing the amount of binder, however the permeability of lime treated clay was almost constant irrespective of amount of binder.
3) In the group column improved ground, the treated column deformed vertically and horizontally due to the concentrated vertical pressure.
4) The consolidation speed of the group column improved ground was greatly influenced by not only the permeability but also the compressibility of treated column. The consolidation speed became faster in the case of the treated column having high compressibility even if the permeability of the treated column was lower than that of the untreated clay.
5) The consolidation phenomenon measured in situ can be explained by the effect of permeability and compressibility of treated column.
6) From long time follow-up observations in Helsinki the ratio of the permeability coefficient of lime-treated clay to that of untreated clay shows to be much lower that that introduced in literature.
7) The field observations fitted to a mathematical model in order to gain proper estimation for the ratio of permeability coefficient between the lime-treated clay and the untreated clay give values from lower than 1 to about 5.
8) This paper recommends the factor 1.0 for the ratio of permeability of lime-treated column and that of untreated clay and the factor 0.1 to 0.5 for cement-treated clays.
9) Cement or lime columns do not act like vertical drains.

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