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Prediction and Assessment on Consolidation Settlement for Soft Ground by Hydraulic Fill

준설매립 연약지반에 대한 압밀침하 예측 및 평가

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요 지

본 연구에서는 해안 준설매립지반에 대한 연약지반 개량사례를 이용하여 연직배수공법 적용시의 현장계측 및 압밀침하 해석을 실시하였다. 대상현장은 원지반위에 대략 10m의 준설매립을 통해 조성된 부지로서 고함수비 및 고압축성의 해성점토로 구성되어 있다. 1년 동안의 현장 계측결과, 당초 설계시의 예측침하량에 비해 매우 큰 압밀침하가 발생하였고, 이 조건에서의 향후 침하거동을 예측하기 위한 추가 압밀침하 해석 및 계측결과를 이용한 역해석을 실시하였다. 상부시공 영향 등에 의해 준설매립지반에는 과다한 전단변형이 발생하였으며, 이에 대한 현장 계측결과의 평가 및 보정을 실시하였다. 압밀해석 및 원지반 조건을 평가하기 위해 실내시험 결과를 이용한 물질함수 분석을 실시하였으며, 최종적으로 부지 인도후의 잔류침하량 및 최종 지반고를 만족시키기 위한 추가 성토고를 산정하였다. 추가 성토이후의 현장 계측결과와 당초 예측했던 압밀침하 거동을 비교하였으며, 이를 통해 당초 예측내용에 대한 검증을 수행할 수 있었다.

Abstract

This paper describes the performance of ground improvement project using prefabricated vertical drains of condition, in which approximately 10 m dredged fill overlies original soft foundation layer in the coastal area composed of soft marine clay with high water content and high compressibility. From field monitoring results, excessive ground settlement compared with predicted settlement in design stage developed during the following one year. In order to predict the final consolidation behavior, recalculation of consolidation settlements and back analysis using observed settlements were conducted. Field monitoring results of surface settlements were evaluated, and then corrected because large shear deformation occurred by construction events in the early stages of consolidation. To predict the consolidation behavior, material functions and in-situ conditions from laboratory consolidation test were re-analyzed. Using these results, height of additional embankment is estimated to satisfy residual settlement limit and maintain an adequate ground elevation. The recalculated time-settlement curve has been compared with field monitoring results after additional surcharge was applied. It might be used for verification of recalculated results.

Keywords : Consolidation analysis, Consolidation settlement, Dredged fill, Marine clay, Settlement monitoring

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1. Introduction

Increasing national necessity for expansion of industrial site together with a general decrease in the number of available areas have created the need for landfills using fine-grained material dredged from the coastal area near. For the construction of national industrial complexes, a large scale reclamation and ground improvement project involving about 20 million square m of soft ground improvement has been under way on the south coast area in Korea.

Land reclamation on the foreshore of existing coastlines often overlies soft clays which require soil improvement to ensure stability during and after construction and to reduce or eliminate undesirable short and long term settlement (Choa et al., 2001). The project is the case of landfills on soft marine clay in the coastal area of Yeosu, southern Korea, and involves ground improvement using prefabricated vertical drains and surcharge. The consolidation settlement of not only the surface reclamation layer but also the original soft clay layer underneath has been continuously measured since the beginning of the work. The predicted results in design stage using various laboratory data are compared with the observed ones considering construction effects, such as heaving and displacement, caused by additional works near. From the field monitoring results, excessive ground settlement has been developed and compared with the value in design stage. This is a serious issue for this project, in which the transfer date of final improved is limited for further construction of industrial facilities. In this study, the magnitude and the rate of the consolidation settlement were reassessed by back analysis of the observed settlement, and results from laboratory consolidation test.

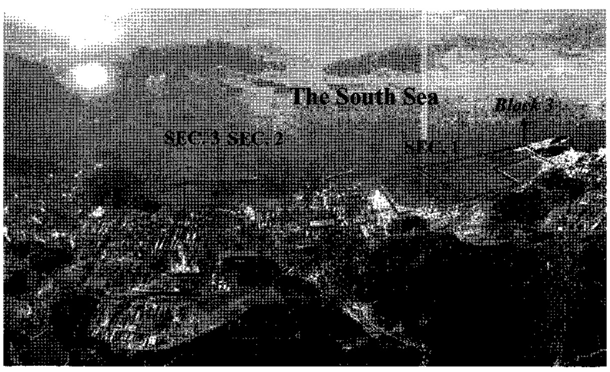


Fig. 1. The site of national industrial complexes project

2. Improving Soft Ground

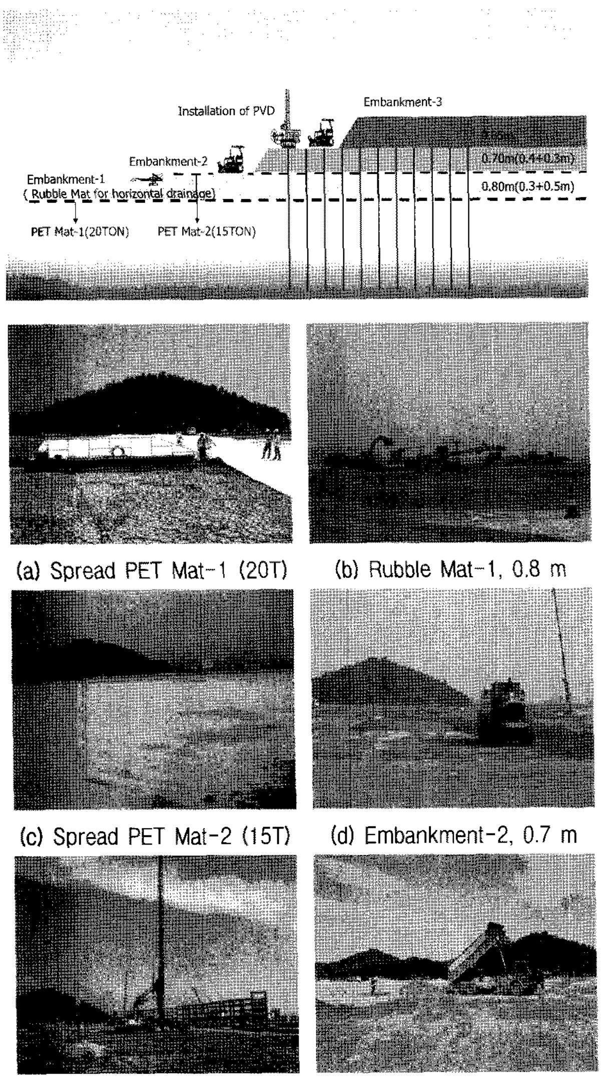
2.1 The Site and Ground Condition

The site for the study is located in the Yeosu national industrial complexes project in Korea. The project comprises land reclamation and ground improvement works to allow for the future construction of advanced chemical and heavy industry complex. Land reclamation works which involved the hydraulic placement up to 20 m of soft marine clay for the formation of 7.8 km^2 land has been conducted from 1996 to 2003 on the original soft ground. The ground consists of upper dredged fill which contained very soft marine clay, up to 10 m in thickness, having high compressibility and high moisture content and lower original clay layer of 3-10 m thickness. The areas for project were divided into 4 sections, and each section was divided into appropriate blocks for efficient construction. For block 3 in section 1, ground improvement by vertical drain in combination with up to 3.5 m thickness of surcharge commenced from September, 2006 is in progress after hydraulic filling of $8{,}300 \times 10^3$ m^3 of slurry completed in Dec. 2003.

2.2 Vertical Drains with Preloading

The use of prefabricated vertical drain with preloading was considered in this project to accelerate the rate of consolidation and to minimize future settlement of the treated area under future load.

Construction procedure for improving soft ground is shown in Fig. 2. Geotextile of PET mat was spread out on the soft ground to get construction capability caused by very low shear strength. With the same reason, rubble mat of 0.8 m height was spread out using conveyer system. Generally, the ground improvement works are carried out in such a way that a specified degree of primary consolidation is attained within the desired time by improving the soil drainage system. It should be required to satisfy final ground level pre-designed for industrial facilities after site transfer, and to limit residual consolidation settlement within 10~30 cm in this project. It corresponds to requirement of site transfer to client companies which have plans to construct industrial facilities. The main variables in design stage are the magnitude of preloading, the spacing of vertical drains, the duration of preloading, and the consolidation parameters of soft marine clay. Prefabricated vertical drains in a width 10 cm were installed at 0.8~1.5 m square spacing depending on the duration of the preloading period. Preloading was subsequently placed to the design height of 2.35~3.5 m for 8~12 month after surcharge placement. In design stage, the consolidation settlement that the requirements for site transfer can be satisfied was expected to develop during 8~12 month. However, there was a great difference between the design value and estimated results from the field monitoring.



(a) Spread PET Mat-1 (20T) (b) Rubble Mat-1, 0.8 m

(c) Spread PET Mat-2 (15T) (d) Embankment-2, 0.7 m

(e) Installation of PVD (f) Embankment-3, 0.85 m

Fig. 2. Construction procedure for improving soft ground

2.3 Field Monitoring

In order to monitor the performance of ground improvement and to verify the original design for improving soft ground, several geotechnical instruments were installed to monitor the degree of consolidation and final settlement. The surface settlement plates were installed just before the installation of vertical drain on the geotextile to ensure construction capability. The multilevel settlement gauges and piezometers were installed at various levels in order to monitor the settlement of various sublayers and pore pressure dissipation.

Surface settlement and pore pressure were monitored at close intervals of 1~3 days during the first three months, and at the wider intervals of 7~10 days during the later part of monitoring. Fig. 3 shows the surface settlement results of P1-2-4, P1-2-5, and P1-2-6 together with the construction activities. These three surface settlement plates were installed in a typical zone with a space of 25 m in order to verify each result by cross review. As shown in Fig. 3, surface settlement of each point shows big differences due to construction events in which large shear deformation may occur by installation of PVD and continuous embankment in the early stages of consolidation. However, from results after 33 days of PVD installation,

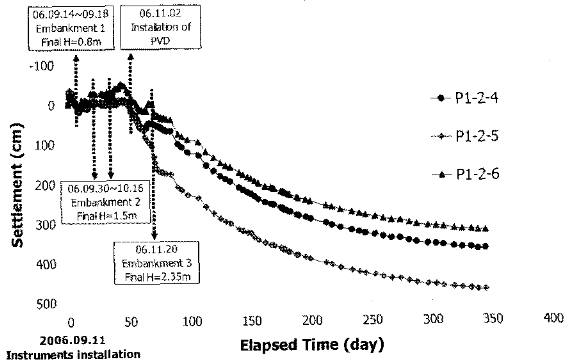


Fig. 3. Monitoring results of surface settlement for zone-1

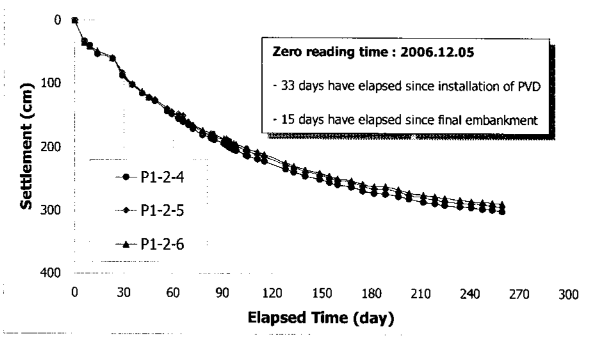


Fig. 4. Monitoring results after zero reading for zone-1

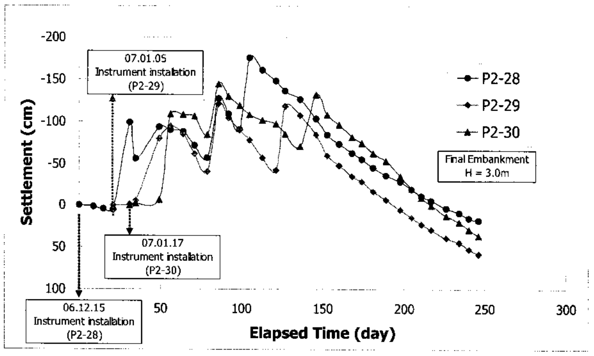


Fig. 5. Monitoring results of surface settlement for zone-2

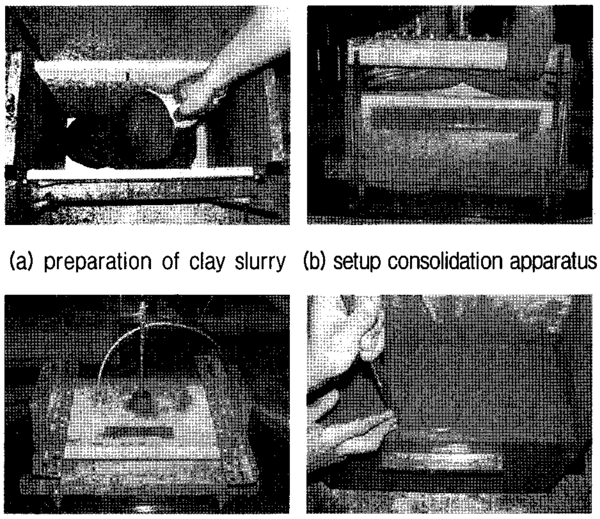
surface settlements of three points show a good agreement as shown in Fig. 4. It is important to note that settlement up to the present has developed over 4.5 m although ultimate consolidation settlement in design stage was predicted as about 3.0 m at zone-1. These disagreements between predicted consolidation settlement in design and monitored results made big trouble for this project, in which the transfer date of final improved site is limited for further construction of industrial facilities.

Fig. 5 shows results of consolidation settlements on surface with surcharge period of 250 days for zone-2. Monitoring period of zone-2 after installation of PVD and continuous embankment is under 3 months. For zone-2, field monitoring results of surface settlement could not be used for the prediction of consolidation behavior and ultimate settlement.

3. Characteristics of the Marine Clay

3.1 Sampling Methods

The most important thing when unexpected excessive



(a) preparation of clay slurry (b) setup consolidation apparatus

(c) consolidation (d) sampling for laboratory tests

Fig. 6. Remolded sample of disturbed clays taken from dredged fill (Yoo, 2007)

settlement developed was to take a proper step for predicting ultimate consolidation settlement. It was required to investigate consolidation parameters and material function by laboratory (Yoo, 2007) and in situ tests.

Undisturbed samples were taken from lower original clay layer of 3-10 m thickness. All samples were carefully sealed on site immediately after sampling. The fresh samples were carefully wire trimmed into specimens for testing in the laboratory. For the upper dredged fill up to 10 m, retrieval of undisturbed sample was impossible because fill material of marine clay was in the state of slurry with high moisture content up to 150%. Disturbed clays were taken from field and remolded samples for laboratory tests were made by large consolidation apparatus under certain effective stress.

3.2 Soil Properties

In accordance with KS standards, natural unit weight, specific gravity, grain size distribution, and Atterberg limits of marine clay at Yeosu were determined as shown in Table 1. For upper layer of dredged fill, test results of disturbed sample taken from in-situ show that average values of the specific gravity, liquid limit and plasticity index are 2.72, 86.3% and 56.5, respectively. Maximum natural water content which is determined by disturbed clay of SPT sampler is 117.9%. For lower layer of original

Table 1. Soil properties of marine clay

Soil properties	Upper dredged fill layer (remolded sample except for water content)		Lower original clay layer (undisturbed soil)	
	Min.	Max.	Min.	Max.
Natural water content (%)	88.1	117.9	65.1	82.5
Passing No.200 sieve (%)	95.8	99.9	97.9	99.1
Specific gravity	2.71	2.73	2.70	2.73
Liquid limits (%)	76.3	96.2	54.5	88.9
Plasticity index	50.8	62.2	31.9	60.3
USCS	CH		CH	

Table 2. Consolidation parameters of marine clay

Soil properties	Upper dredged fill layer (remolded sample)		Lower original clay layer (undisturbed soil)	
	Min.	Max.	Min.	Max.
Initial void ratio, e_o	2.3	2.9	1.6	2.3
Compression index, c_c	0.83	1.22	0.79	1.07
Vertical coefficient of consolidation, c_v(cm^2/s)	5.0E−04	9.2E−04	3.0E−04	3.5E−04
Horizontal coefficient of consolidation, c_h(cm^2/s)	6.0E−04	9.7E−04	4.6E−04	6.5E−04

marine clay, laboratory tests were conducted using undisturbed sample.

3.3 Consolidation Parameters

The preconsolidation pressure, the compression index, vertical coefficient of consolidation and permeability were determined by conventional oedometer tests as well as 150 mm diameter CRS (Constant Rate of Strain) tests using both undisturbed and remolded samples. With the use of vertical drain, the horizontal coefficient of consolidation becomes one of the most important consolidation parameters. Laboratory tests with 60 mm, 100 mm, 150 mm diameter were also performed to measure coefficient of consolidation in horizontal direction, c_h. In-situ test, conepenetrometer dissipation tests (CPTu) were used to measure c_h as well as pore water pressure. Results of consolidation parameters are shown in Table 2.

3.4 Material Function

The most important parameters governing the primary consolidation calculations are the void ratio-effective stress and void ratio-coefficient of permeability relationships obtained from laboratory consolidation tests (Stark et al., 2005).

Cargill (1985) and Poindexter (1988) describe the recommended laboratory testing procedure to obtain these relationships. These relationships may be used to assess initial effective stress at each sub-layer for consolidation calculation and coefficient of consolidation at each effective stress. Defining these relationships from low effective stress level requires two different laboratory consolidation tests of self-weight consolidation and conventional oedometer. Stark et al. (2005) used results of self-weight consolidation test to find the void ratio-effective stress and void ratio-permeability relationships at effective stresses less than about 0.96 kPa. Also, results of conventional oedometer test were used to find the void ratio-effective stress and void ratio-permeability relationships at effective stresses greater than about 0.96 kPa. In this research, conventional oedometer, Rowe cell and CRS tests were performed for these relationships.

Fig. 7 presents the void ratio-effective stress and void ratio-permeability relationship measured using self-weight

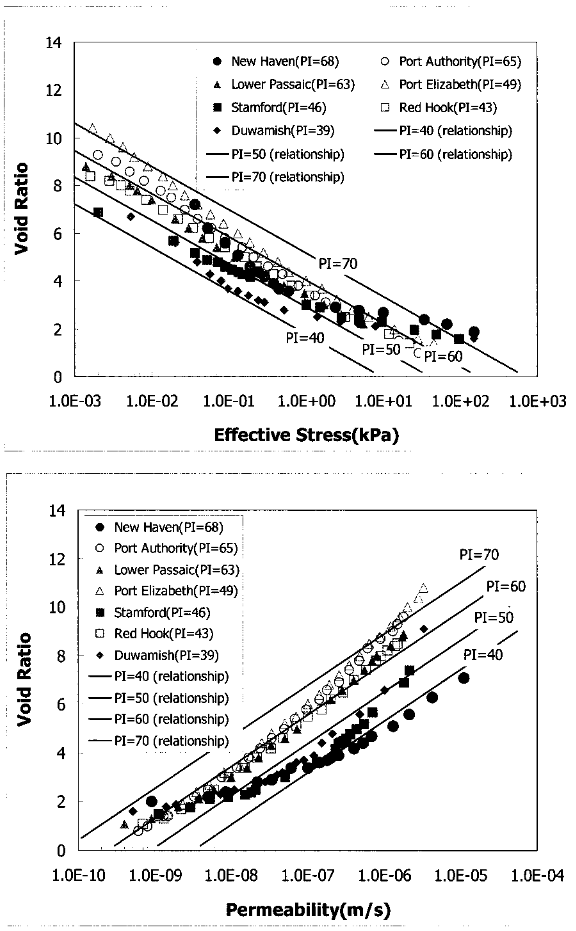


Fig. 7. Void ratio-effective stress and void ratio-permeability relationship for inorganic clays of high plasticity (Stark et al., 2005)

consolidation and typical oedomenter tests for 19 dredged material types from 17 placement sites (Stark et al., 2005)

Fig. 8 presents material function for void ratio-effective stress and void ratio-permeability from Lab. tests in this study. For void ratio-effective stress relationship, material function shows a good agreement with empirical relationship of high void ratio, e > 2.3. A series of results that describe effective stress and permeability with void ratio less than 2.3 show difference of a considerable margin.

4. Prediction of Consolidation

As mentioned above, settlement after 350 days has developed over 4.5 m although ultimate consolidation settlement in design stage was predicted as about 3.0 m at zone-1. These disagreements between predicted consolidation settlement in design and monitored results made

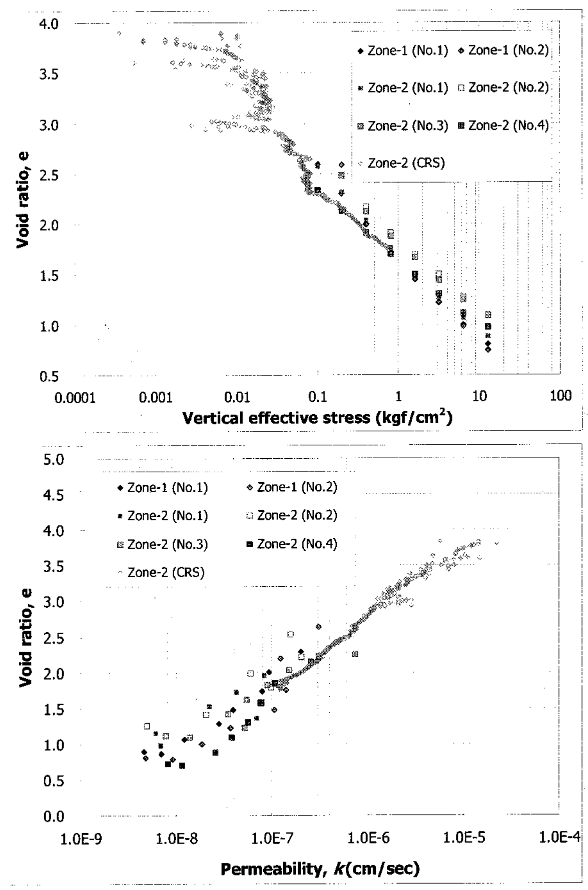


Fig. 8. Void ratio-effective stress and void ratio-permeability relationship from Lab. tests

big trouble for this project, in which the transfer date of final improved site is limited for further construction of industrial facilities. In this particular situation, overriding concern was to predict the consolidation settlement with time including magnitude of ultimate settlement.

In conventional consolidation theory, strains are assumed to be small or in a mathematical sense, infinitesimal (Gibson et al., 1981; Mesri et al., 1974).

This is a background to use constant coefficient of compressibility, a_v and the coefficient of volume compressibility, m_v when calculating consolidation settlement. Primary consolidation settlements in design stage of this project were calculated by m_v. However, this method has limitations for considering large strain problem associated with a great change of effective stress because of its nonlinear stress-strain relationship (Gibson et al., 1981; Terzaghi et al., 1996).

The primary consolidation settlements of upper dredged fill and original clay layer were recalculated using compression index, c_c. Initial effective stresses of sub-layers were estimated from both void ratio-effective stress relationship and natural water content-void ratio relationship. The magnitude of settlement was calculated on several subdivided layers in order to be able to predict the ultimate settlement accurately. The c_v and c_h values basically were derived from material function of laboratory tests, and different values were applied to calculation by effective stress level.

Field monitoring results gave a good agreement with time-settlement relationship although it shows fluctuation in initial part caused by shear deformation with upper construction activities. At first, consolidation settlement with time was recalculated using material function from Lab. tests. There were a some differences between recalculated value and real field monitoring results during 350 days. The back analysis was conducted by modifying material function until recalculated curve fits to field monitoring results. The recalculated and monitored surface settlements for zone-1 are shown in Fig. 9.

Major contract terms for site transfer in this project are that residual settlement after site transfer should be less than 10 cm, and final ground elevation should be the same as the original design value. For satisfying ground elevation in design stage, additional surcharge was required to compensate excess ground settlement.

However, additional surcharge may act as an external load, and this may give rise to more settlement. In instances when it appears that too much consolidation settlement is likely to occur, it may be desirable to apply some additional surcharge loading in order to eliminate or reduce the post-construction settlement. It was important to estimate how much additional surcharge was required to satisfy all contract terms for site transfer. Essential facts related with estimation of settlement, such as settlement history, final ground elevation, date of site transfer, load condition after completion, and allowable residual settlement, were considered carefully. Fig. 10 shows the consolidation settlement with time in case of applying additional surcharge at time elapse of 429 days. The additional surcharge with the height of 3.2 m was applied for satisfying residual settlement limit and final ground level.

The recalculated time-settlement curve shown in Fig. 9 has been compared with field monitoring results from 85 to 350 days. Fig. 11 includes some monitored results after additional surcharge with the height of 3.2 m was applied. It might be used for verification of recalculated results.

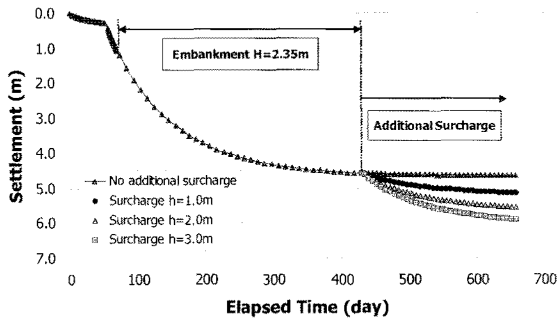


Fig. 10. Prediction of time-settlement for each surcharge height

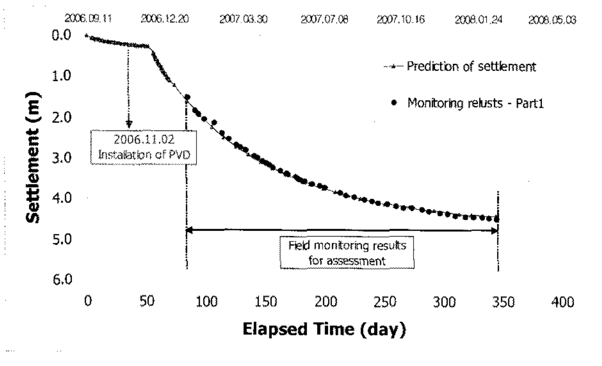


Fig. 9. Recalculated and monitored time-settlement curve for zone-1

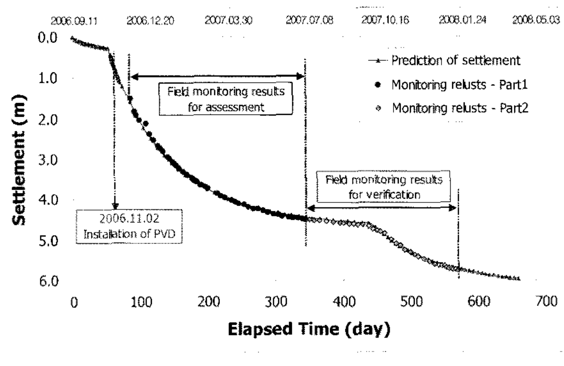


Fig. 11. Additional field monitored time-settlement curve for zone-1

5. Conclusion

The project of landfills on soft marine clay including ground improvement using prefabricated vertical drains and surcharge was carried out on the foreshore of southern Korea where a significant thickness of highly compressible soils existed on the seabed. Ground improvement works were required for both upper dredged fill layer and lower seabed soils. Excessive settlements, which could not be expected in design stage have been developed. It was required to reassess monitoring results because it showed large fluctuations in magnitude of settlement due to shear deformation. The material functions related to consolidation and permeability characteristics of the marine clay were investigated from laboratory and in situ tests. Application of different consolidation parameter by effective stress level from material function gives a good result for prediction of settlements with time for very soft marine clay.

The primary consolidation settlements with time of upper dredged fill and original clay layer were recalculated, and the back analysis was conducted by modifying material function until recalculated curve fits to field monitoring results. Method of additional surcharge loading was adapted as a technical measure to reduce the post construction settlement, and speed up consolidation process before site transfer. Amount of additional surcharge loading was evaluated carefully in consideration of final ground elevation, date of site transfer, and allowable residual settlement.

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