기술초대석 | 한국지반공학회지 | Vol.23, No.9 | pp.10~20

Accelerated Consolidation Methods for Ultra-soft Clay Ground Using Reduced Neutral Stress



Masaaki Kiyama
Penta-Ocean Construction Co., Ltd.

Hiroshi Shinsha
Penta-Ocean Construction Co., Ltd.

Shunji Kusumoto
Penta-Ocean Construction Co., Ltd.

1. Introduction

When soft clay deposited on seabed is dredged and reclaimed into a landfill, it will turn into sludge with water content more than twice the liquid limit and form ultra-soft ground with almost no shear strength, on which people would have difficulty even in walking. Such ultra-soft ground entails the following challenges from a geotechnical point of view.

1) Development of a method to increase its shear strength without applying shear stress to the ground
2) Development of a method to decrease its mass in order to increase its dredged soil intake capacity

While the vacuum consolidation method can address both issues, the dewatering method can address the issue (2). As shown in Figure 1, the vacuum consolidation method and dewatering method are means to improve the consolidation of ground by decreasing atmospheric pressure or water level so that such decreases in the neutral stress will act on the clay soil as load. There is no risk of shearing failure of the ground because such decreased neutral stress all acts as isotropic stress. Therefore, these methods are believed to be best suited for improving the consolidation of ultra-soft ground.

In this paper, we give an example of construction using the vacuum consolidation method with capped drains, which was invented by our company, Penta Ocean Construction Co., Ltd. and has been

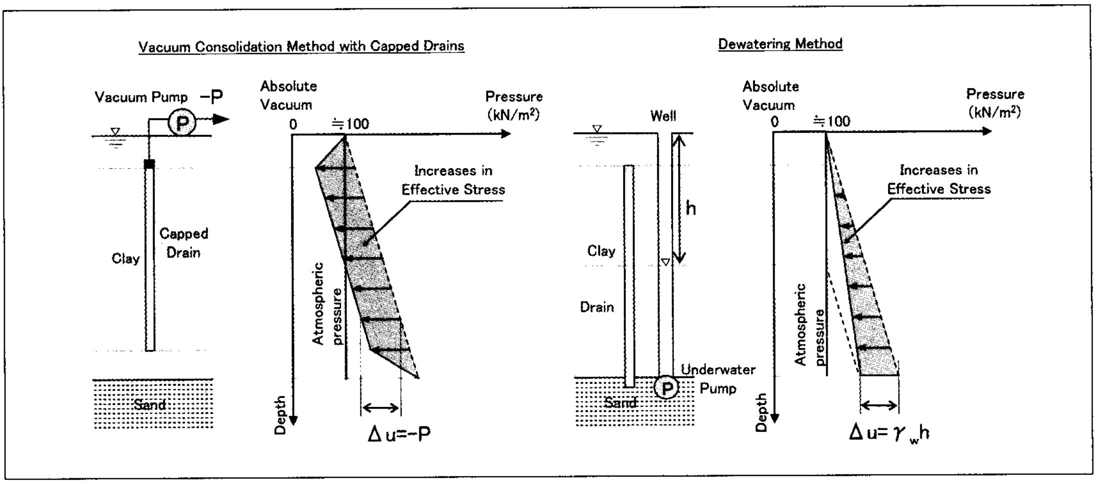
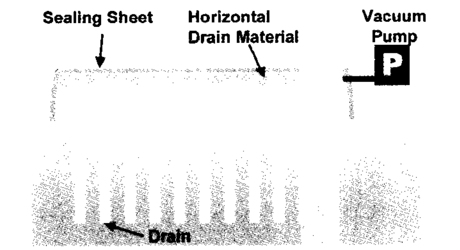
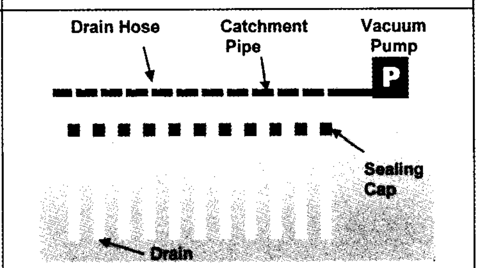


Figure 1. Operating Stress Pattern Diagram

Table 1. Classification of Vacuum Consolidation Methods

Method	Improved Sealing Sheet Method	Capped Drain Method
Schematic (Example)		
Advantage	· Can improve up to the ground level.	· Sealing sheets not required. · Can be installed both underwater and on land.
Disadvantage	· Requires preventive measures against air leakage at edges of sealing sheet. · Hard to install in a place where installation of sheet is difficult, such as on water or on mud.	· Requires preventive measures against air leakage at openings for drain installation. · Surface layer (sealing layer) remains unimproved or poorly improved.

increasingly deployed at various construction sites in Japan, as well as to briefly introduce an outline of the accelerated consolidation method with a combination of the plastic board drain by floating (PDF) method and dewatering method based on one of the authors' (Dr. Kiyama) experience in Yumeshima island, the Port of Osaka.

2. Vacuum consolidation method with the use of capped drains

2.1 Overview

The vacuum consolidation method was developed in Sweden in the 1940s[1]. Table 1 shows the classification of 2 types of the vacuum consolidation method[2] and their respective advantages and disadvantages. The sealing sheet method is widely used, by which the ground surface is covered by a sealing sheet so that negative pressure will be applied on the ground. However, it is deemed difficult to apply the sealing sheet method to the ultra-soft ground or submerged soft ground where scaffolding cannot be set up because the use of sealing sheets is essential to this method. On the other hand, the application of the capped drain method[3] involves the materials shown in Photo 1 and it is executed in accordance with the following procedures.

1) Pre-fabricate drain units equipped with a cap and a drain hose on top of each cap at the factory.
2) Deliver the pre-fabricated drain units to the construction site.
3) Drive in each drain unit into the ground until its cap reaches the level of approximately 1m below the clay soil surface.
4) Connect the drain hoses remained above ground to catchment pipes and apply negative pressure by using a vacuum pump.

This method is characterized by the use of approximately 1m-thick clay layer below the clay soil surface as a sealing layer and therefore there is no need to use a sealing sheet. We believe to the best of our knowledge that the following prerequisites are required in order for this method to work.

i) The coefficient of permeability of the clay soil portion to be used as a sealing layer shall not exceed approximately 10^{-5}cm/s[4].
ii) The water level shall be maintained above the cap

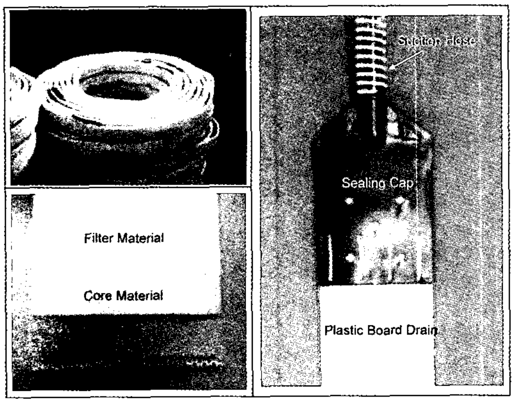


Photo 1. Capped Drain Unit

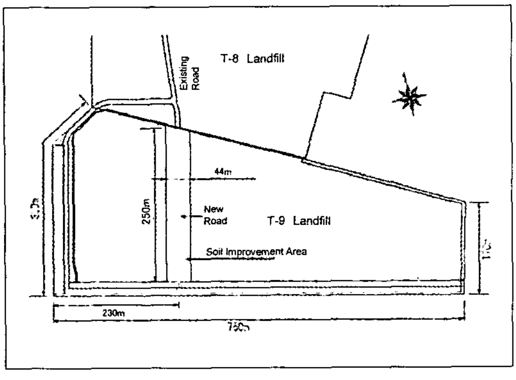


Figure 2. Plan View of Landfill

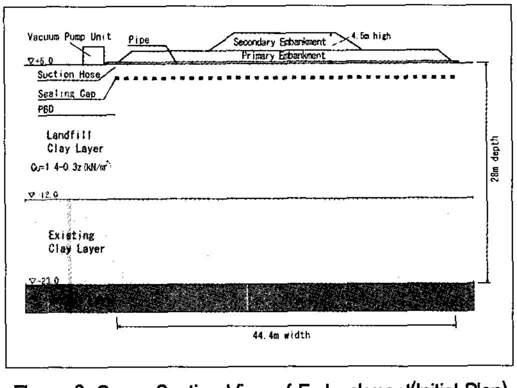


Figure 3. Cross-Section View of Embankment(Initial Plan)

Table 2. Soil Properties(before Improvement)

Soil Layer Classification	Depth (Thickness)	w (%)	γ_t (kN/m^3)	Cu (kN/m^2)	Cc	Cv (cm^2/day)
Landfill Clay Soil (1)	0~5.0 (5.0)	119	14.0	Cu=1.4	1.026	180
Landfill Clay Soil (2)	5.0~17 (12.0)	120~129	14.0	Cu=1.4+0.3*z	1.026	180
Existing Clay Soil	17.0~28.0 (11.0)	72~122	14.8	Cu=4.0+0.7*z	1.035	130

(Z=0 at EL=0.0)

depth.

2.2 Example of road embankment construction

We applied the vacuum consolidation method with the use of capped drains to road embankment construction at the center of a landfill, in which soft dredged clay had been reclaimed[5)6)]. Figure 2 and 3 show a plan view of the landfill and a cross-section view of the embankment (initial plan) respectively. The ground to be improved was 44.4m wide and 250m long, within which drain units were driven in up to a depth of 28m arranged in the shape of square, 1.2m on a side.

The foundation was ultra-soft ground, in which dredged clay had been injected on top of existing clay soil and the soil properties are as shown in Table 2. As you can see, the water content of the surface layer was as high as 120% and its shear strength was extremely low before improvement. As a result, during the planning stage, it was proven that if the embankment was built as per the planned cross-section, its stability could not have been secured because strength increase would not have been sufficient after the implementation of the proposed improvement using the vacuum consolidation method. Therefore, as shown in Figure 4, we executed the 2-stage vacuum consolidation work, by which we laid a sand mat after the first-stage improvement using the vacuum consolidation method, built primary embankment to the extent that no shear failure could occur to the embankment and then applied the vacuum consolidation method again.

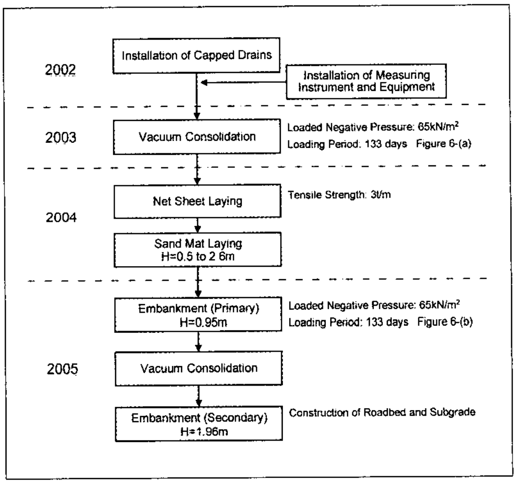


Figure 4. Constuction Flow

For the installation of capped drains, we used a

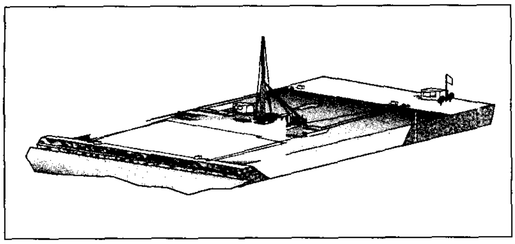


Figure 5. Drain Installation Pattern Diagram

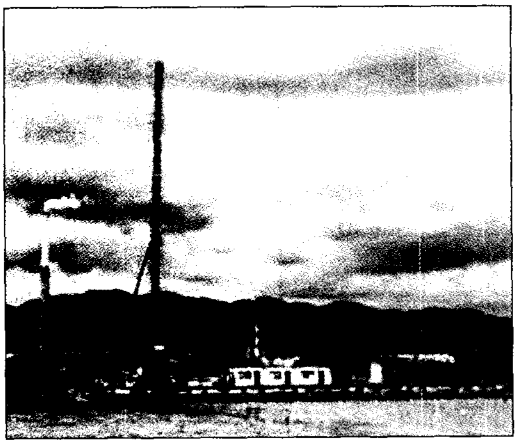


Photo 2. Drain Installation Machine Rigging on a Floating Pontoon(PDF Pontoon)

drain installation machine rigging on a floating pontoon (10m wide, 55m long and 1.2m high) called Plastic-board Drain by Floating (PDF) method. Its construction pattern diagram is shown in Figure 5 and a full view of the pontoon is shown in Photo 2.

Figure 6 shows the ground settlement profile after vacuum consolidation. The ground subsided in the shape of a bowl due to vacuum consolidation. In addition to the initial settlement of approximately 3.7m, the central portion subsequently settled further by approximately 1.0m after sand mat laying, primary embankment building and second vacuum consolidation. Figure 7 shows the soil properties after the improvement. While the clay soil layer was unconsolidated at the beginning and its shear strength was 1.4kN/m^2, it increased up to Cu=20~50kN/m^2 after the improvement through primary embankment and vacuum consolidation.

The construction was completed with secondary embankment and the site is currently being used as a road.

3. Accelerated consolidation method combining the use of plastic-board drains (PDF method) with the dewatering method

3.1 Overview

This is a method whereby a PDF pontoon is launched in a dredged clay landfill site to drive in plastic board drains (hereinafter referred to as PD/PDs) to the dredged clay soil layer until they reach the sand layer laid on seabed by artificial means. Subsequently, a pumping well installed on the sand mat layer is activated so that the water level in the sand mat layer is reduced and downward currents are set up inside the PDs. This action helps increase consolidation load as well as accelerate settlement so as to enable a large volume of new dredged clay to be taken in within a short period of time.

Points to keep in mind when applying this methods are to ensure the continuity of the PDs and the sand

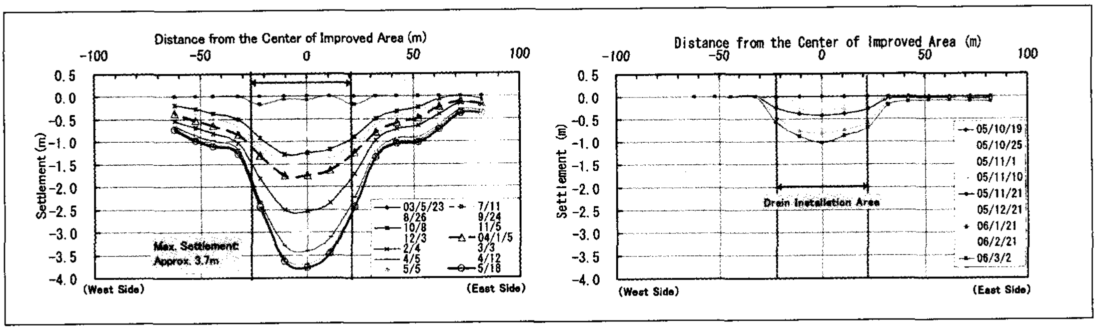


Figure 6. Ground Level Settlement Profile

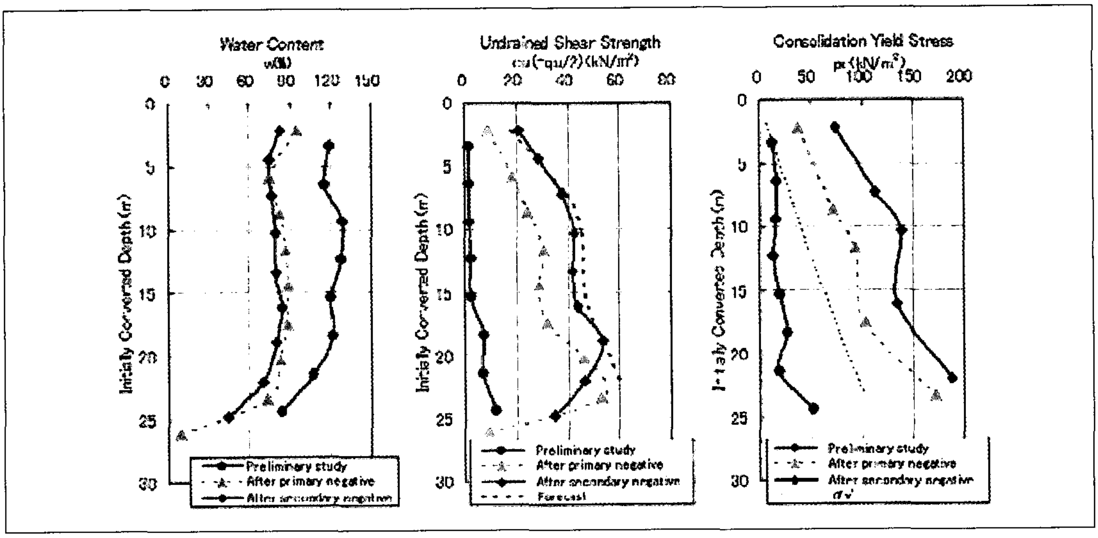


Figure 7. Soil Properties after Improvement

mat layer and not to let the water retained on top of the dredged clay layer seep into the PDs. Specifically, we confirmed the first point based on the mandrel penetration resistance at the time of PD installation. The installation was easy because the penetration resistance of the dredged clay soil layer was clearly different from that of the sand mat layer. To ensure the second point, we decided to scrap and seal a drain groove at the top of each PD by thermocompression bonding. While this method was deployed in an area of approximately 100ha and brought about significant results, we would like to introduce hereafter an outline of the site experiment work, which was executed prior to the main construction.

3.2 Site experiment work

The experiment work site is located in Yumeshima island, Osaka Bay (refer to Figure 8). We conducted a preliminary study to check the condition of the

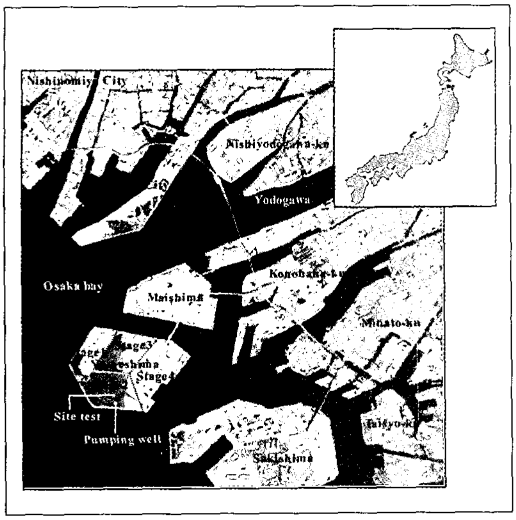


Figure 8. Experiment Work Location Map

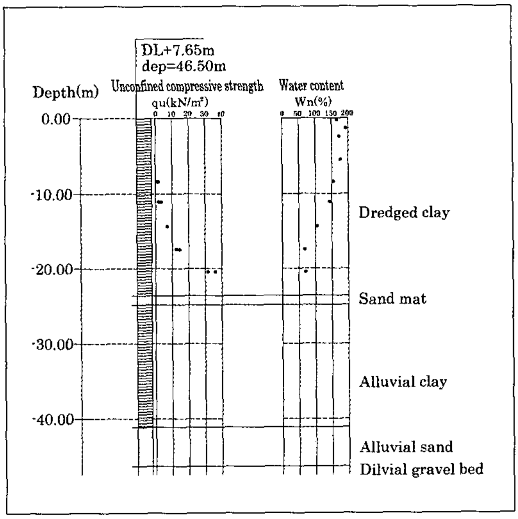


Figure 9. Histogram of Soil Types

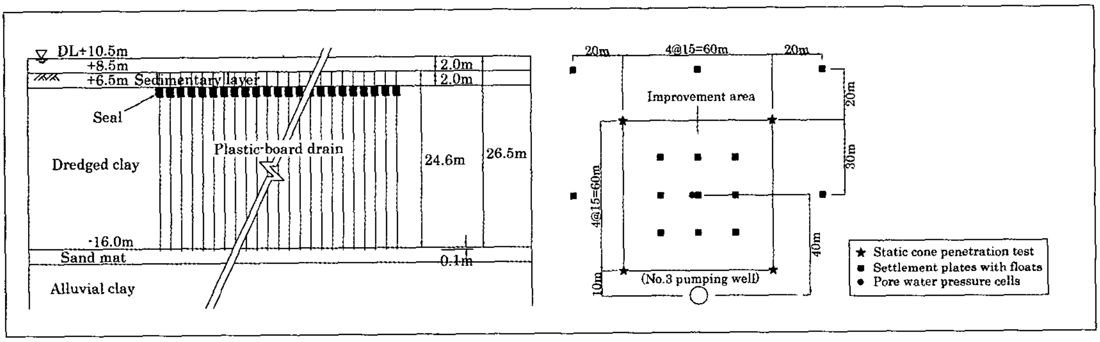


Figure 10. Schematic View of Experiment Work

ground by collecting undisturbed samples (Figure 9). The dredged clay soil was taken from fairways, anchorage areas and rivers and the dredged clay layer so reclaimed was as thick as 24m.

The experiment work was done according to the following procedures. We firstly drove in PDs (24.6m-long, 2484nos in total, covering an area of 60mx60m), activated a pumping well immediately thereafter to reduce the water level of the sand mat layer and measured the settlement and pore water pressure (refer to Figure 10). The pumping well was located approximately 10m away from an end of the work area. The settlement of the area improved by PD was 3.0m to 3.5m bigger than that of an unimproved area (refer to Figure 11) and therefore we were assured of the effectiveness of this method. The settlement shown in Figure 11 is the settlement of the dredged clay soil layer only and was calculated by subtracting the settlement of an outer pipe of settlement observation pipes (indicating the

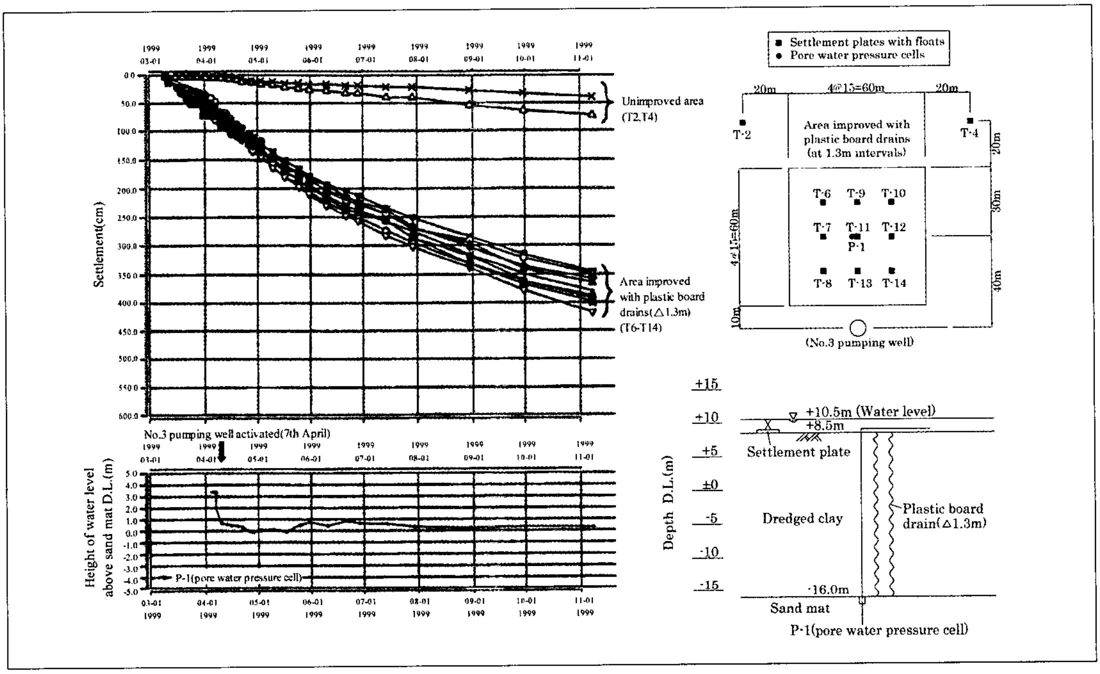


Figure 11. Experiment Work Observation Results

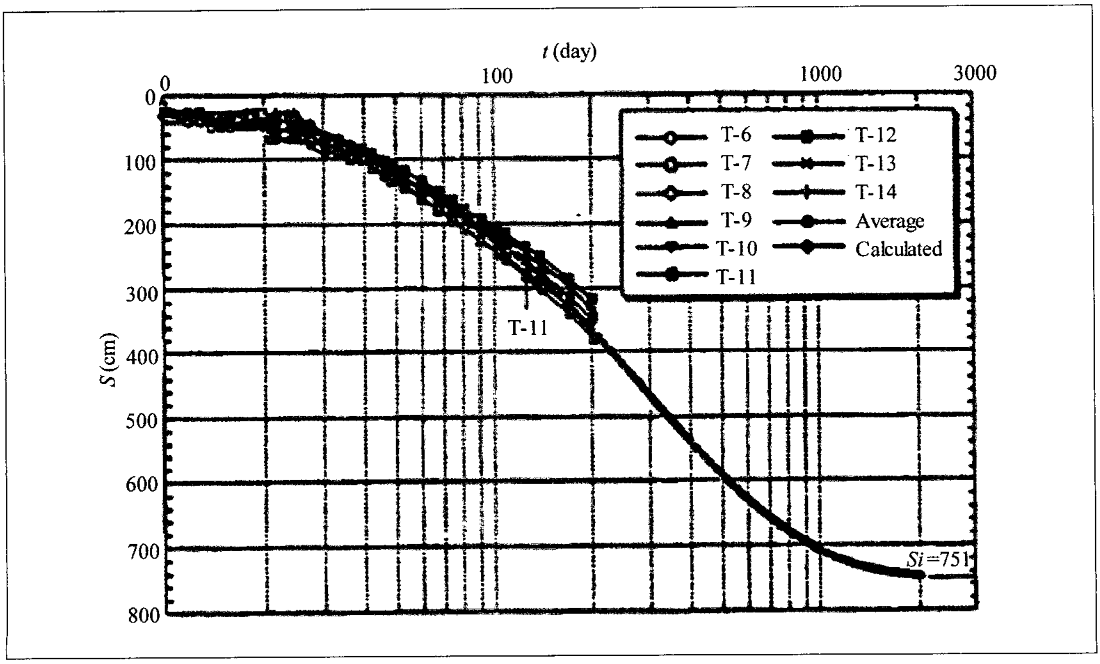


Figure 12. Comparison between Calculations and Measured Settlement

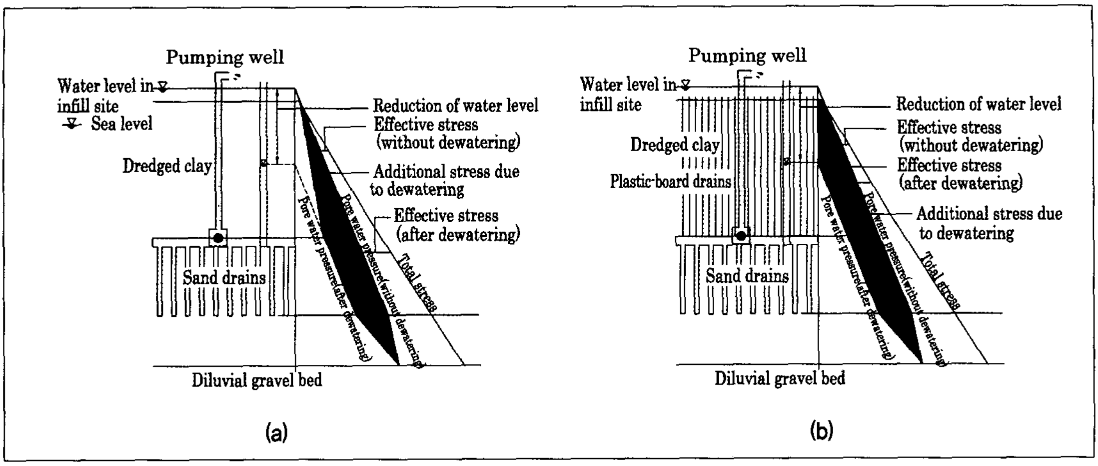


Figure 13. Improvement Principle Pattern Diagram

settlement of sand mat layer and deeper layers) from the level of a settlement plate with floats (indicating the settlement of ground level).

Figure 12 shows calculated settlement and observed settlement curves against the actual observation time. They significantly coincide with each other. Please refer to the literature cited for supplemental information on the settlement calculation process and a comparison between variations in the water content and calculated values.

Let us examine effective stress increases that can be obtained through the reduction of water level. Generally, the colored portion shown in Figure 13 (a) is said to be an increases in the effective stress but if combining with the use of PDs like this case, such a colored portion as shown in Figure 13 (b) is considered an increase. Furthermore, looking at the settlement measured on site against time, the actual settlement occurred cannot be explained unless the colored portion shown in Figure 13 (b) is taken into account. It would appear that the effective stress is increased by forcibly setting up downward currents inside PDs. We further believe that even potential negative pressure effects can be expected above the lowered water level.

4. Conclusions

We have given an example of both the vacuum consolidation and dewatering methods as some of representative examples of the neutral stress reduction method. We believe that both methods brought about satisfactory results in the cases described in this paper. There tend to be the increasing number of embodiments of the vacuum consolidation method in Japan in recent years. As it is an indisputable fact that the neutral stress reduction method still causes frustrations among users of not being able to personally verify, unlike an embankment load, the effective stress for consolidation obtained, we will continue our efforts to collect data and hope to improve its maturity in future. Our vision of the future is to enable concurrent reduction in atmospheric pressure and water level. We have verified the question of whether both can concurrently act as effective stress in indoor experiments and presented in an essay[10]. If this method is established, it will be highly effective in improvement of marine clay soil ground at a depth of 10m or more and will have a potential for being applicable to wide-ranging construction works, such as building revetments, quays and breakwaters and increasing the depth of fairways and anchorage areas.

Last but not least, we would like to express our gratitude to Korean Geotechnical Society for giving us such an opportunity. We would also like to extend a special thank to Ph. Doc., Kim Jae-Young from AMCO Co., Ltd. for his kind cooperation in this submission.

References

1. Kjellman.K.: Consolidation of clay soil by means of atmospheric pressure, Proc. Conf. on Soil Stabilization, M. I. T. Cambridge, pp.258-263. 1952
2. H. Shinsha, H. Yoneya, T. Nagatsu: Changes and transition in the vacuum consolidation method, "Soils and Foundation", Journal of the Japan Geotechnical Society, Vol. 54, No.7, pp.16-18, 2006(Japanese)
3. H.Yoneya, T.Shiina, H.Shinsha: Improvement of soft ground applying vacuum consolidation method by expecting upper clay layer as sealing-up material, Soft Ground Engineering in Coastal Area, pp.275-283, 2003
4. H. Takahashi, H. Shinsha, M. Yoshikawa, T. Shiina: Airtightness retention effects of the vacuum consolidation method on peat layers, 62nd Japan Society of Civil Engineers Annual Academic Lectures (in the process of submission), 2007(Japanese)
5. J. Nakaoka, H. Yoneya, K. Hitoi, H, Motonaga: Application of the vacuum consolidation method to unconsolidated ground reclaimed from dredged clay soil (Part 1), 40th Meeting for Presenting Papers on Geotechnical Studies, pp.1053-1054, 2005(Japanese)
6. J. Nakaoka, H. Shinsha, Y. Fujiki, H. Yoneya: Application of the vacuum consolidation method to unconsolidated ground reclaimed from dredged clay soil (Part 2), 40th Meeting for Presenting Papers on Geotechnical Studies, pp.1055-1056, 2005(Japanese)
7. M.Kiyama, A.Oshima, S.Higashi, K.Harada: Accelerated consolidation method for dredged clay combining the use of plastic board drains with the dewatering method, International Seminar (Kochi), 2000
8. M.Kiyama, A.Oshima, S.Higashi, K.Harada: The New' Accelerated Consolidation Method' Combining the Dewatering and plastic-board-drain by Floating (PDF) Method, KIG Forum,

Kyoto, 2000

9. M. Kiyama, T. Tokuhira, A. Oshima, S. Azuma, K. Harada: Dredged soil volume reduction technology by the use of vertical drains at repository sites, Japan Geotechnical Society: Collected papers from symposia on latest studies on and practical side of clay soil ground, 2002,5(Japanese)

10. T. Shiina, H. Yoneya, H. Shinsha, T. Tsuchida, M. Kiyama: Effects of the neutral stress reduction method on the improvement of underwater clay soil ground where vertical drains are installed, 38th Meeting for Presenting Papers on Geotechnical Studies, pp.1079-1080, 2003(Japanese)

연회비 인상에 관한 안내

우리학회는 지난 15년간(1993년부터 2007년) 정회원 및 특별회원 등의 연회비를 동결 · 유지하여 왔으나 부득이 물가 상승 등을 고려하여 지난 임시 대의원 회의(2007. 05. 18)에서 학회운영규칙을 개정하여 아래와 같이 회비를 인상하기로 하였습니다.

– 아 래 –

학회운영규칙 제2장 회원 및 회비

제7조(입회금 및 연회비) 정회원의 입회금 및 회비의 종별에 따르는 연회비는 다음과 같다.

현 행		변 경	
입회금	15,000원	입회금	30,000원
정회원의 연회비	20,000원	정회원의 연회비	30,000원
학생회원의 연회비	10,000원(학부생에 한함)	학생회원의 연회비	10,000원(학부생에 한함)
특별회비의 연회비 ;		특별회비의 연회비 ;	
• 특급	1,000,000원 이상	• 특급	2,000,000원 이상
• 1 급	500,000원 이상	• 1 급	1,000,000원 이상
• 2 급	300,000원 이상	• 2 급	500,000원 이상
• 도서관 회원	50,000원	• 도서관 회원	50,000원

◎ 종신회비 : 연회비의 12배 산정 납부　　◎ 시행일시 : 2007년 9월 1일