報 告

Vacuum Consolidation Method – Worldwide Practice and the Latest Improvement in Japan

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ABSTRACT: Vacuum consolidation method is a technique of applying vacuum suction to an isolated soil mass to reduce the atmospheric pressure in it, thus by the way of reducing the pore water pressure in the soil the effective stress is increased without changing the total stress. By improving construction techniques, as well as developing analytical methods for designing, the technique has become an effective and economical method for soft ground improvement and capable to conduct in various site conditions. Researches are also extended to other application fields such as acceleration dewatering and consolidation of fluid-like materials. Conducting of numerous vacuum consolidation projects has been tried in many countries in the world, through that practical experiences are accumulated, which would have significant importance in improving its efficacy and advancing the technique. For the purpose of gaining experience, numbers of published documents and research papers on vacuum consolidation practice from leading countries in this field of technology have been reviewed. This paper summarizes and compares various vacuum consolidation systems with emphasizing on system specification and configuration, design and construction practice, and introduces the newest improvement of this technology in Japan.

Keywords： soil improvement, vacuum consolidation, surcharge, vertical drain, horizontal drain

1. Introduction

A technique using atmospheric pressure as a temporary surcharge was principally proposed by Kjellman 50 years ago (Kjellman, 1952), and was worked out by the Royal Swedish Geotechnical Institute as a method for fine grain soil improvement. The method is based on the idea of applying vacuum suction to an isolated soil mass to reduce the atmospheric pressure in it, thus by the way of reducing the pore water pressure in the soil the effective stress is increased without changing the total stress.

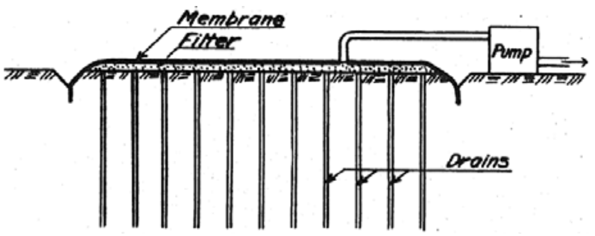

Figure 1　Swedish vacuum method (Kjellman, 1952)

However, for several following decades the method had not widely been applied due to various difficulties, mainly in maintenance of effective vacuum pressure during treatment. With improvement in the methodology and producing high quality vertical drains and airtight sheets, vacuum consolidation method became popular in many countries. Furthermore, together with clarifying the actual mechanism of vacuum preloading, improving construction techniques for drain installation and vacuum pumping operation, monitoring process, as well as developing analytical methods for designing allowed the method be applied effectively and economically and capable to conduct in various site conditions whether on-land or underwater. Even that, to make the method more beneficial, researches are kept continuing in order to increase its efficiency and to extend to various application fields. Various international symposiums on vacuum consolidation have been conducted for the purpose of better understanding of the technique and technology transfer.

Beside Sweden as pioneer in this field of technology, great contributions in development and advancing vacuum consolidation method to various fields of applications come from China, the U.S., Japan and other European and Asian countries. Most recently, a Japanese group has successfully developed a new technique for heightening the vacuum pressure in the soil. Learning experience from

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those countries would have significant importance in advancing the technique and improving its efficacy in various application fields. This paper reviews vacuum consolidation practice from various countries with some comparison in the system configuration, design and construction, and introduces the newest improvement in Japan.

2. Various Vacuum Consolidation Systems and Construction

Various vacuum consolidation systems are developed for number of applications. As primary application of vacuum consolidation method is consolidation and stabilization of soft clayey ground, most of the systems developed for these purposes are basically similar to the one originally developed by Norwegian Geotechnical Institute (NGI), though every system may have some specific features. When the vacuum consolidation method is extended to other applications with different working conditions and different treated materials, the systems require specific features and/or special designed construction machines. Moreover, vacuum consolidation applied in on-land and under-water conditions are principally different in equivalent load as the vacuum is applied on ground surface or under water table, relatively.

2.1 On-land vacuum consolidation system for soft ground improvement

Principally, a vacuum consolidation system consists of a system of drains vertically installed from ground surface into the treated soil mass to prescribed depth, a surface drainage system including a granular medium (sand mat) and horizontal drains, and collector pipes leading to a vacuum pump system for transmission of vacuum to the soil as well as discharging water and air out of the treated soil mass. The vacuum treated soil mass is isolated from surface by an airtight membrane and if required laterally protected from leakage by cut-off-walls. Table 1 presents three typical vacuum consolidation systems utilizing different types of vertical drains.

(1) Vertical drains

In any on-land system, numbers of drains are installed vertically from ground surface in triangular or square grid pattern at selected spacing into the treated ground to prescribed depth. The vertical drains can be different in shape, material, structure and drainage properties. Typical types of drains are prefabricated board drain (familiar in ground improvement under name of "PVD"), cylindrical pipe drains (named as Menard vacuum transmission pipe, VTP) and sand drains. PVD is the most popular type of drains used in vacuum consolidation nowadays. Sand drains have been used since early development of vacuum consolidation in China and some other countries, however due to various disadvantages this type of drain has been almost completely replaced by the PVDs.

As the drain is one of the most important things that make the method to be technically and cost effective, the development of drain material is continued. Japan introduced newly developed highly permeable drain material for the PVD. Moreover, considering environmental impacts, some kinds of degradable drains such as bamboo drains (Singapore) and biodegradable plastic drains (Japan) are introduced but still not popularly employed in vacuum consolidation.

These systems are basically for on-land sites, although there are a few cases applying to shallow under-water condition (Sasaki, 2002).

(2) Surface drainage

Normally it consists of a granular layer (commonly a sand mat) and a system of perforated collector pipes with/without interconnected horizontal drains embedded in. Horizontal drains connect the vertical drain tops to the main vacuum pipe. The type and layout of surface drainage system can be modified in various systems. The sand mat layer is commonly of 0.3-0.8m in thickness (depending on sand permeability, selected spacing of vertical drains and surface trafficability), though occasionally it maybe thicker to serve as working platform. Occasionally, the sand mat might be omitted and replaced by drainage geotextile layers (Japan). Horizontal drains can be different in types (corrugated flexible PVC pipes or PVD board drains), as well as in arrangement. See Table 1 for different surface drainage arrangements in Chinese and Menard systems.

(3) Sealing techniques for vacuum isolation in treated soil mass

The airtightness of the system strongly influences the attained vacuum pressure and the efficiency of the system.

Table 1 On-land vacuum consolidation systems for soft ground improvement

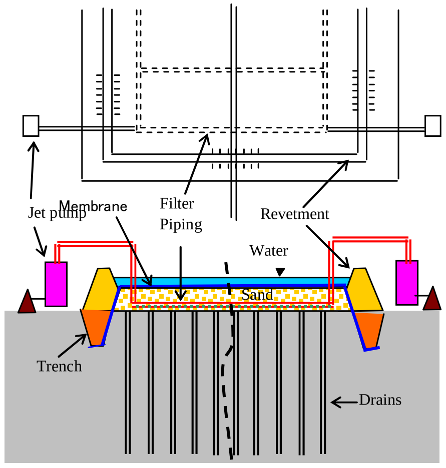
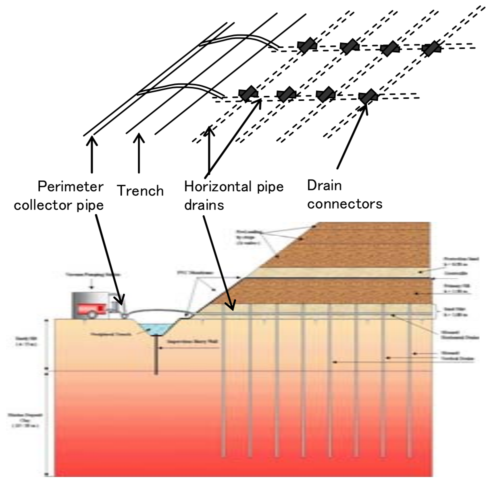
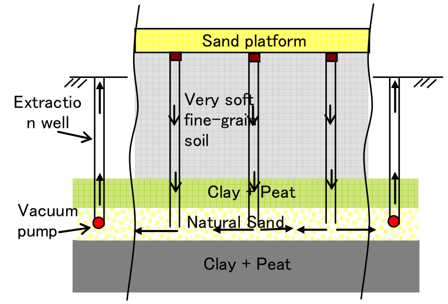
System type		Systems using PVD	System using cylindrical pipes	System with Vertical Sand Drains
Image		 *(After TPEI report, China 1995)*	 *(www.Menard-Soltraitement.com)*	 *Modified after Van Mighem 1999 (www.terra-et-aqua.com)*
Typical system		Chinese system and other similar systems in the US., Europe and Asia countries (including Japan system)	Menard MVC (France) developed and employed by Menard Soltraitement in France and foreign countries	Developed by SILT NV (Belgium) since 1990s' Used in Belgium
Special features		Principally work as original designed system Most common type of drains PVD, high-speed installation The membrane is covered with water to sustain high vacuum pressure and prevent the membrane aging… Individual treatment area: standard 6,000 – 10,000 m^2 Conventional construction machines	Principally work as original designed system Menard cylindrical drains of high discharge capacity Applying primary fill beneath membrane to increase sealing and stability of system. Individual treatment area: standard 5,000–7,000 m^2	Vertical sand drains of large diameter; Use natural bottom sand layer as horizontal drainage and for applying vacuum pressure; Vertical drainage downward;
System configuration	Vertical drainage Horizontal drainage	PVD (card board drain), 100 mm x 3–4 mm, spacing 1.0–1.2 Sand mat + manifold from main filter collector pipes with fish-bone branches PVC pipes (China) or PVD (Japan)	Menard cylindrical pipes VTP, ϕ50mm; spacing 1.4–1.5m Sand mat + perforated PVC pipes in two perpendicular directions connected to peripheral collector pipe;	Vertical sand drains, ϕ300 mm, spacing 2.75 m, capped Bottom natural sand layer.
	Surface membrane Peripheral trench Additional sealing Lateral confining	PVC airtight sheet (one or several layers); Clay mix slurry (China) or in-situ impermeable soil (Japan) Clay revetment above the trench for retaining soil fill or extracted water discharged above the membrane; Clay mixed cut-off-wall;	PVC woven geotextile membrane; Bentonite aquakeep slurry and backfill water on top; Primary fill (1.5 m) on top of sand beneath membrane; Bentonite slurry wall or sheet piling;	Membrane is not required as sand drains are capped on top by clay and silt;
	Vacuum pump specification	ϕ 48Jet pump + 3HA-9 centrifugal water pump of 7.5kW; 1000–1500 m^2/pump, vacuum pressure >80 kPa (China)	Menard vacuum pump station MS25 (25 kW) 5,000–7,000 m^2/pump station, designed vacuum 75 kPa	2 rows of vacuum pumps arranged along the sides of improved area (railway foundation)
		Air-water separation high vacuum pump system (Japan) 2000–2500 m^2/pump, effective vacuum pressure >80 kPa		
	Instrumentations	Automatic controlling, recording and measuring system	Automatic controlling, recording and measuring system	Not specified
Applications		Various projects of ports, airports, highways, bridges, buildings, petroleum, chemical, sewage & power stations…	Various projects of roads & highways, bridges, buildings, petroleum and power stations, sewage facilities…	Seldom used nowadays, however beneficial in special conditions for soft ground improvement.
Typical project		The East Pier Xiang Port (Tianjin, China 1987) Sanriku Motorway project (Tohoku, Japan 2003)	Road 837 (France, 1994) Kimhae Sewage treatment facility (S.Korea, 1995)	Railway foundation Spoorwegzate (Belgium, 1999): improvement of soft disposal sediment (Sludge)

Table 2 Various types of drain utilized for vacuum consolidation

Drain Type	Prefabricated Board Drain (PVD)	Cylindrical Pipe Drain (VTP:Vacuum Transmission Pipe)	Sand Drain
Special Futures	・The most major type ・High conductivity ・Easy and high-speed installation ・The least disturbance ・High cost performance	・High conductivity k=7.0×10^{-2} cm/s ・High integrity preservation for dynamic force	・Common used before, rarely nowadays ・High conductivity ・Difficult to obtain and maintain quality
General Spacing	China:1.2～1.3 m depending on c_h Japan:0.7～1.2 m depending on c_v	1.4～1.5m depending on c_h	China: 1.2m (drain diameter 70 mm) Belgium: 2.7m (drain diameter 300 mm)
Applicable Depth	more than 40 m	more than 50 m	more than 10 m
Materials	・Grooved polypropylene core and non-woven textile filter	・Plastic cylindrical core with grooves ・Special geotextile protection, filter	Fine Sand
Cross-section	Rectangular 100 mm×3～4 mm	Round, diameter 50 mm	Round, various diameter (70 - 300 mm)
Major Countries	China, U.S., European and Asian countries	France and some other countries (Designed by Menard)	China and some other countries

The common practice is using PVC airtight membranes (2-3 layers) to cover the entire treatment area and they are welded at the site. China developed single air tight membrane layer more than 100,000m^2. A geotextile layer may be laid on the ground surface before covering by membrane to avoid damage. To complete the sealing, the membrane edges are keyed in peripheral trench excavated to the depth at least 0.5m below the ground water level and filled with impervious slurry, which can be clay mix slurry (China), Bentonite Polyacrolyte slurry with water on top (French Menard), or in-situ excavated clayey soil (Japan).

Beside that, different systems may utilize different technique for additional sealing. Among that is a practice of construction of compacted clay revetment above the trench to retain the water/fill placed on the top of the membrane. This placement of water is useful not only in increased sealing of the system, but also in preventing aging of the membrane and minimizing damage from traffic and wildlife, as well as affecting as a surcharge. Another technique is from Menard system, in which a 1.5m thick primary fill is constructed directly on the top of the sand mat beneath the membrane for increasing the stability and sealing of the system. The fill will maintain a non-submerged action beneath the membrane even when it has been settled below the original ground water level, therefore the vacuum intensity will not decrease during treatment (Cognon et al., 1996).

In case of pervious soil layer exists near the ground surface, the common technique for lateral confining is construction of cut-off-walls. According to China experience, a clay mix slurry wall (0.7m thick, permeability <1x10^{-5} cm/s) constructed by the deep mixing method throughout pervious layer and at least 1.5m inside the clay layer would be effective. Other types of material such as Bentonite slurry (Menard) or specialGeolock (Holland BV) are also applicable.

(4) Vacuum pump system

Generally, a high efficiency vacuum pump system equipped with discharge pump is used to provide suction to the soil and to discharge the air-water out through the system of pipes and drains.

In China, the common vacuum pump has been replaced by the ϕ 48mm Jet Pump (7.5 kW) with 3HA-9 centrifugal water pump, which can generate a vacuum pressure greater than 90 kPa. For Menard system, a vacuum station consists of a specifically designed high-efficiency vacuum pump acting solely on the gas phase in conjunction with a conventional vacuum pump allowing liquid and gas suction. In Japan, Maruyama Industry Ltd. and Hazama Co. group successfully employed a specially designed vacuum pump system, which can separate water and air collected in the main and sub-separator tanks by means of build-in discharge water pumps, thus sustaining high under-sheet vacuum pressure during treatment.

(5) Instrumentations

In any vacuum consolidation system, various instrumentations are necessary to control the system operation as well as to monitor the performance of the treatment including vacuum pressure, optimal pore water pressure, discharged water volume, settlement and lateral displacement, which are useful in judgment of the time to stop the vacuum pump, and controlling stability of embankment construction.

2.2 Vacuum consolidation systems for dewatering fluid-like materials

In order to apply for accelerated dewatering and consolidation of new hydraulic fills, sewage and slug, lagoons and mine ponds mud etc. vacuum consolidation system with special features to deal with fluid-type materials and special construction machines capable to work whether on-land or underwater conditions are necessary. Typical vacuum consolidation systems applied for acceleration dewatering and consolidation of fluid-like materials are illustrated in Table 4.

(1) Systems with vertical drains

Originally, the US developed vacuum consolidation system (since 1970s) for treating hydraulic fills consists of multi-stage dike constructed on the surface of natural soil for containing dredged disposal (on-land confined disposal facility; CDF). During dumping of hydraulic fill, horizontal drainage layers (drainage sheets or sand) are placed. Several vertical drainage wells are constructed thereafter and connected to vacuum pump through a system of slotted collector pipes which can be arranged on the surface or at the bottom of the CDF depending on whether drainage is upward or downward, respectively. Later, the USACE (US) modified the system by using PVDs instead of vertical drainage wells for applying in underwater condition for dewatering contaminated hydraulic dredged materials at Newark Bay Sub-aqueous CDF project. As the vertical drains are capped at tops and drainage was allowed downward using submerged vacuum pump, membrane was not required for sealing (Thenavagayam, 1996).

Beside that, underwater vacuum systems utilizing vertical drains for consolidation of soft seabed soils in offshore condition include the one investigated at the Imperial College, London proposed for submarine consolidation at Chek Lap Kok, Hongkong (Harvey, 1997) and the one recently developed in Japan (Shinsha et al., 2002). Those systems are characterized by a system of vertical drains installed throughout underwater soft seabed soils with the tops of the drains being capped and buried in the soil and connected to a pipe system leading to vacuum pump, so that membrane for sealing is not required.

(2) Systems with lateral drains

As the treated materials are very soft to fluid-like, specially designed construction device for working in water condition and to inserting the drains horizontally in the soil is necessary. Typical systems of this type are those developed in Japan and Belgium.

Penta-Ocean Co. (Japan) developed a system using special designed floating boat with a winch and a guide leader to install simultaneously several (generally 4) card-board drains laterally and parallel in layers at the spacing of 0.7-1.5m within the new hydraulic fill. With the boat cruising back and forward, the installation is completed. The installation leaves a 1.5m thick surface layer of treated material above the upper drains to serve as natural sealing for the system. Each lateral drain, which may be 300m in length, has a hose to connect to the vacuum pump through a header. The technique is limited by the thickness of treatment of 5-6m as only few drain layers can be employed. Its effectiveness for dewatering and consolidation has been verified in several cases including an actual improvement project of slurry-like soda ash at a disposal site of 40,000m^2 (Shinsha et al, 1996).

Table 3 Types of vacuum systems

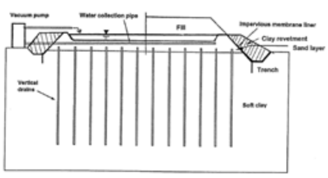
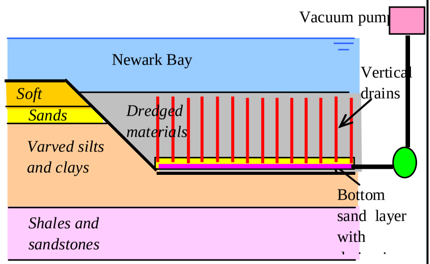
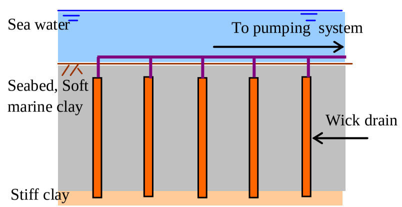
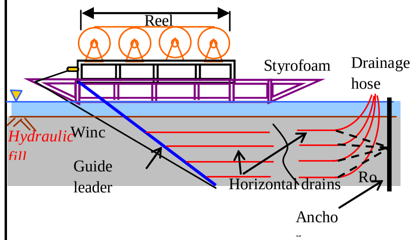
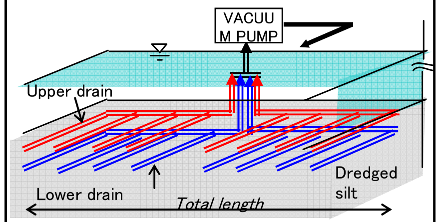
System Type	Chinese Type	Menard MS5 type	Japanese Type
Image			
Vacuum Pump Specification	・Generated vacuum pressure: >90 kPa ϕ 48Jet pump + 3HA-9 centrifugal wate Power 7.5 kW	・Generated vacuum pressure: 80 kPa Menard MS25 type Power 25 kW	・Generated vacuum pressure: up to 90 kPa Air-water separation high vacuum system
Special Futures	One vacuum pump responsible for a treatment area of 1000-1500 m^2	Special designed vacuum pump acting solely on the gas phase in conjunction with conventional vacuum pump allowing liquid and gas suction. A vacuum pump station is responsible for 5000-7000 m^2.	Able to separate water and air, which results in high vacuum performance in treated area. One vacuum pump responsible for 2000-3000 m^2 treated area.

Table 4 Vacuum Consolidation Systems for Accelerated Dewatering of Fluid-like materials

System type	Systems with vertical drains		System with Horizontal Drains	
	System with PVD, downward drainage	System with PVD, upward drainage	System with horizontal PVD drains	System with horizontal pipe drains
Image	 (After Sandiford et al., 1996)	 (After Harvey, 1997)	 (After Shinsha et al, 1996)	 (After Van Mieghem et al., 1999)
Typical system	Developed by USACE (U.S., 1996) according to original system with vertical and horizontal drains developed in the US since 1970s.	1) Imperial College, London (1997) proposed for application at Check Lap Kok (Hong Kong) 2) Penta-Ocean Co. Japan (recently)	Developed by Penta-Ocean (Japan) since 1987-1988	Developed by SILT NV (Belgium)
Special features	Applicable for underwater or on-land conditions Vertical drainage downward; Require initial construction of dumping facility and engineering placement of bottom drainage layer; Not require membrane for surface sealing	Under water system, offshore condition Vertical PVD (Alidrains) capped at top and buried in the soft seabed clay, installed down to the depth of stiff clay. Water depth 10m Vacuum pressure 50 kPa (supposed) Not require membrane for surface sealing	Applicable in offshore or on-land conditions Horizontal drains, easily and reliably installed horizontally and parallel in 4 layers using floating barge with winch and guide leader. Treatment depth: 5-6m Settlement: up to 50% of initial thickness; After treatment w_0 = 80-90% w_L Not require membrane for surface sealing	Offshore condition at water depth from 1-25m Horizontal drainage Use special designed lay-barge equipped with plough for inserting drain tubes horizontally. High speed and easily installation Not require membrane for surface sealing
Configurations: Vertical drainage	Vertical strip drains, capped at top, spacing 1.5m	Vertical Wick drains buried in the seabed clay	Not used	Not used
Configurations: Horizontal drainage	Engineering sand layer with embedded drain pipes installed at the bottom of CDF before placing dredged material.	Horizontal pipe system connecting all vertical drains to submerged vacuum pump	Horizontal board drains spacing 0.7-1.5m installed within dredged fill after fill placement.	Two layers of horizontal drain tubes, spacing 1.5m connected to collector piles led to vacuum pump
Configurations: Surface sealing	A layer of hydraulic fill left above the drains' tops	A soft soil layer above the capped vertical drains	Top soil layer of 0.65m thick	Top silt layer 0.5-1.0m thick
Configurations: Additional sealing	Capping the vertical drains	Capping the vertical drains		
Configurations: Vacuum pump	Submerged vacuum pump	Submerged vacuum pump system	On-shore	Vacuum pump and submerged discharge pump
Applications	Dewater & consolidate dumping soils to increase storage capacity of confining disposal facilities.	Consolidate and stabilize off-shore soft marine clays in reclamation project	Dewatering and consolidating hydraulic dredged fills or slurry-like wastes	Dewatering and consolidation of dredged silt to increase the storage capacity of disposal facility
Typical project	Feasibility investigation for applying in project at Sub-aqueous CDF Newark bay, New Jersey (US)	Experimental trial for drain application feasibility at the site of Check Lap Kok (Hong Kong)	Experimental trial at reclaimed hydraulic landfill, Treatment of slurry-like soda ash disposal site	Actual treatment at Anwerp Port project (Belgium)

SILT NV (Belgium) developed an underwater vacuum consolidation system using special designed lay-barge with plough construction device to insert drain tubes horizontally in very soft silt. This makes the technique easier to execute and less expensive than the use of vertical drains. The drain tubes have to be inserted at least 1.0 m underneath the top of the silt to assure minimum leakage of water above the silt into the drain tube. Collector tubes are laid on the shore connecting all the drain tubes. A specially designed vacuum pump maintains pressure efficiency of 80-90% in the drains. The system can be applied in the condition of 1-25m water depth. The technique was employed in a project at the Anwerp Port in Belgium in 1996 for extracting water from basin of dredged silt over an area of 120,000m^2, which brought a gain of 20% in storage capacity of the basin. (Van Mieghem et al., 1999). Furthermore, researches on application of this technique for accelerating consolidation and stabilizing underwater slopes and embankments are carried on.

3. Vacuum consolidation design and construction experience

Principally, design of vacuum consolidation can be based on consolidation theories (Terzaghi and Barron theories). Finite Element analysis (FEM) is used to model the soil stress-strain behavior. Design parameters (individual block area, sealing measures, drain spacing, depth, effective vacuum pressure and combined surcharge, vacuum pumping period…) are essentially dependent on the site conditions, soil properties, the used vacuum and drainage system, the purpose and other requirements of the project. Therefore, experience is of great importance in selection of optimum design to satisfy both technical and cost effectiveness.

(1) Individual vacuum treatment area and the treatment area by single vacuum pump

Depending on size the total treatment area is divided into blocks for sealing in individual vacuum treatment. In Chinese practice, the block size normally varies at 6,000-10,000m^2, although it is feasible from minimum 1,000m^2 to maximum 30,000m^2. For each block, one or more vacuum pumps are equipped providing that an area for individual vacuum pump is standardized at 1,000-1,500m^2. However, in case of presence of thick pervious layer near the surface causing lateral leakage of vacuum, the individual treatment area should be reduced (to 600m^2 according to experience from project of Yaoqiang Airport, China, Tang & Shang, 2000). For Menard design, the standard area for a Menard vacuum pump station is 5000-7000m^2, and several vacuum pump stations will be used according to the size of treatment area. In Japan, however, the individual treatment area is specified at 2,000-2500m^2, which will be supported by a single vacuum pump.

(2) Drain spacing:

For each treatment, the vertical drain spacing has to be determined according to the coefficient of consolidation of the treated soil and the time requirement. Generally, optimum spacing should be selected by balancing between the time and the cost. Different vacuum consolidation systems utilizing different types of drains (PVD or cylindrical pipes) may find different range of optimum spacing.

According to Chinese experience from numerous projects in the Port of Tianjin, for most of the treated soils with $c_h \cong$ 1-2.5 x 10^{-3} cm^2/sec and the time available for vacuum pumping was generally 5 months, spacing of PVD drains was generally selected at 1.2-1.3m. However, it might be shortened to 1.0m for soils of $c_h \cong$ 0.6-0.7 x 10^{-3} cm^2/sec, or even to 0.5-0.85m in cases of restricted time (Liu, 1995). In Japan, it is specified that the PVD spacing should not larger than 1.2m, but from 0.7-1.2m corresponding to soil c_v value. Actual practice in Japan indicated that the selected PVD spacing is mainly at 0.8-1.0m. The highest spacing for PVDs was 1.5-1.8m in the Pier 300 Port of Los Angeles project (Thenavagayam et al., 1996).

For Menard practice, spacing for cylindrical drains is commonly selected at 1.4-1.5m for most soils with c_h = 0.2-2 x 10^{-3} cm^2/sec, though it may vary from 1.0m to 1.7-1.8m in some projects depending on soil properties and other factors.

(3) Effective depth

Depending on soil profile and required improvement, the drain length is determined. For most of projects in China and Japan, the treatment depth was within 20m, with exception cases up to 25-30m. However, the maximum treatment depth up to 43m has been evident in Menard project at Kimhae Sewage Treatment Plant (South Korea), which suggests that the effective depth is only limited by considering the maximum depth to which vertical drains can be installed at reasonable price. Anyway, vertical drain must not penetrate into the permeable layer, but shall be terminated at about 1m above the bottom of the soft soil layer (Thenavagayam, 1996) or >0.5m according to TPEI China (Liu, 1996), while Japan recommends at least 2m considering uneven bottom of treated soil layer with regard of construction condition control.

(4) Effective vacuum consolidation pressure

The effective vacuum pressure inside the soil (or so called under-sheet vacuum pressure) is normally lower than the vacuum generated in the pump. For on-land systems, efficiency of vacuum loading of 70-80% is evident. Based on actual experience, designed vacuum pressure in Menard MVC system is 75 kPa, while a value of 80 kPa is used in China design though greater values of efficiency (80-95 %) are reported. In Japan, a minimum value of 60 kPa used to be recommended for design. However, together with using highly airtight membrane and highly permeable drain material, introduction of special designed air-water separation vacuum pump system allows attaining a stable effective under-sheet vacuum pressure as high as 90 kPa during treatment (Sandanbata et al., 2004).

(5) Determination of soil parameters

Compression index C_c, and coefficient of consolidations c_v, c_h are the most important soil parameters used in design for vacuum consolidation. In China, they are normally obtained from conventional laboratory consolidation tests on undisturbed samples. According to China experience, it is also recommended to use the C_c value form e-p' consolidation curve for settlement calculation instead of using m_v or E_s converted from this curve (Liu, 1996).

The coefficient of consolidation c_v and c_h can be obtained from conventional consolidation tests on undisturbed samples, but sometimes is derived from calculation of field permeability coefficients and laboratory compression coefficients. However, when the parameters with high accuracy are required, the field measured settlement-time curve at the early stage of consolidation is used to simulate fitting.

(6) Consolidation degree, vacuum pumping duration

Generally, based on calculated final settlement and consolidation analysis, the vacuum pumping duration is determined so as to achieve a prescribed degree of consolidation and/or allowable settlement rate. The use of Finite Element method (FEM) in consolidation analysis and design is not widely used in practical works because of difficulty in obtaining satisfactory soil parameters, while experience showed that using Terzaghi and Barron theories could practically satisfy the requirement of most ordinary projects in China (TPEI, Liu 1995) as well as in Japan. For convenience, in many vacuum consolidation projects the ratio of observed settlement to calculated final settlement is adopted as the degree of consolidation of soil at the time (Liu, 1995). However, acknowledging that the effect of vacuum loading is controlled largely by pore water pressure changes, it is necessary to analyze the pore water pressure variations and use it for assessment of the degree of consolidation.

In Menard design, the period for vacuum pumping is determined as the time required to reach a “target settlement”, which is determined as 100% of primary consolidation plus 10 year of secondary consolidation under the designed load with a guarantee of 10cm post-treatment settlement over the next 10 years. Estimation of “target settlement” is based on laboratory primary and secondary consolidation curves and the actual settlement curve obtained during treatment.

Experience showed that in most vacuum consolidation treatment (treatment depth up to 20m) without or with small surcharge, the duration of vacuum loading varied from 3 to 5 months. However, it should be noted that, when vacuum is combined with high embankment loading (many cases in Japan) the vacuum pumping duration is normally extended in order to satisfy stable embankment construction at allowable rate.

(7) Combined surcharge load

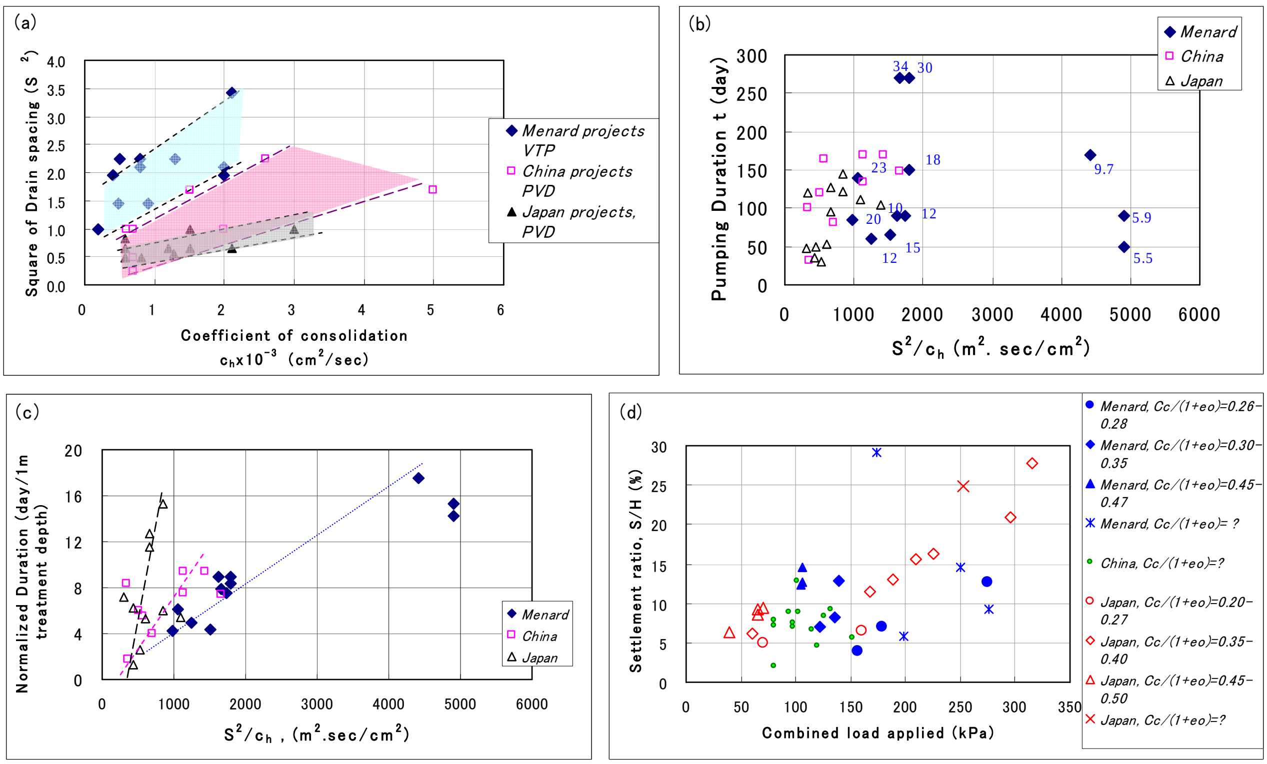
Combination of vacuum loading with surcharge to increase the applying load is widely employed. Surcharge fills up to 5-6m were reported from number of projects worldwide. China considered the maximum surcharge load to combine with vacuum is a problem of economical comparison to be dealt with detailed situations. Maximum fill height up to 15.5m equivalent to 150kN/m^2 surcharge was combined with vacuum loading in Menard project at Kimhae (South Korea).

On the other hand, the vacuum induced inward lateral compression is utilized to solve problems of excessive lateral displacement and instability of embankment foundation or slopes. In Menard project of construction Highway A837 Saintes-Rochefort, building up a 9m high embankment on very loose soil was made possible within less than 3 month. Experience in Japan proved that under support of high vacuum pressure, continuous rapid construction of a 12.5m high embankment could be completed successfully within 3 and a half months (Sandanbata, et al 2004).

Comparison of actual vacuum consolidation designs for typical systems utilizing PVD (China and Japan projects) and cylindrical VTP drains (Menard's projects) are illustrated in Figures 2 (a-d). Typical designs of vacuum consolidation in number of projects are summarized in Table 5. The data were sited or interpreted from tables, graphs or texts from numbers of published documents and papers.

Fig.2 (a) compares the actual selected drain spacing S (plotted in term of S^2) and the range of average c_h values of the treated soils. In general, distribution of data points from each data set (China, Japan, Menard) can be bounded by two lines, where the upper line represents the range of normal design whereas the lower one represents the cases of restricted construction time. It is clear that the selected drain spacing is not only dependent of soil properties, but also of the drain type and design criteria such as available time (for cost effectiveness). The actual pumping duration (generally considered as the time to reach about 90% consolidation degree) is plotted against the value S^2/c_h in Fig.2 (b) for various cases with each data point being labeled with its treatment depth. However, no clear trend was observed suggesting that in vacuum consolidation horizontal drainage might not be the unique process.

When pumping duration is normalized to the treatment depth as plotted in Fig.2(c), there are clearer trends approximately represented by a line for each data set. It suggests that drainage in vertical direction may also control the rate of vacuum consolidation. Different lines of different data point sets might indicate relative differences in design criteria or effectiveness of the systems. Also in cases of high embankment, the vacuum



Figures 2　Comparison of vacuum treatment design from various projects of Menard, China and Japan

(Note: c_v are used instead of c_h in plotting Japan data set as they usually used in Japan designs)

Table 5　Typical vacuum consolidation designs from various projects

a) Menard Vacuum Consolidation with vertical transmission pipes (cylindrical VTP)

Project	Treated Area (m^2)	Soil Properties w_o (%)	$C_c/1+e_o$ (ave.)	Ave. c_h $\times 10^{-3} cm^2/s$	Vacuum consolidation design Sand blanket(m)	Drain Spacing(m)	Treated depth Ave, (m)	Vacuum (kPa)	Fill (m)	Surcharge (m)	Pumping duration (days)	Resulted Settlement Ratio (%)
Ambes1(France)	390	140-860	0.45	0.40	0.8	1.40	5.5	80	1.3	0.0	50	12.4
Ambes2 (France)	21106	140-861	0.45	0.40		1.40	5.9	80	1.5		90	12.7
Lomme (France)	8130					1.50	7.2	80	1.0		50	1.1
Ambes3 (France)	17550	45-57	0.28	0.51		1.50	9.7	80	2.8	3.0	170	7.0
Lamentin1(France)	17692	112-347	0.47	2.10		1.85	10	80	1.5		90	14.5
Hamburg (Germany)	238000	180-250		0.20		0.5-1.0	12	80	5.5		60-150	29.2
Ipoh Gopeng (Malaysia)	2600	70		1.30		1.50	12	80	7.0		90	5.8
Bangbo (Thailand)	30000	105-130	0.30	0.48		1.20	18	80	3.5		150	12.8
Kuching (Malaysia)	12000	60	0.26	0.90		1.20	15	80	3.0	2.0	65	4.0
A837(1) (France)	44500	52-75	0.27	2.00		1.40	20	80	2.5	3.0	85	7.0
A837(2) (France)	10000	60	0.27	2.00		1.2-1.45	23	80	3.3		140	7.1
Wismar (Germany)	15000	80-250				1.20	19	80	1.5-2.5	0-8	90	9.3
Jangyoo (S.Korea)	70000	80-150	0.27	0.80		0.8-1.5	30	80	3.0	0-7	270	14.5
Kimhae (S.Korea)	83580	80-150	0.23	0.80	1.0	0.9-1.4	34	80	1.5	3-6.5	270	12.7

b) China Vacuum Consolidation with Prefabricated Vertical Drains (PVD)

	Area (m^2)	w_o (%)	e_o	Ave. c_h $\times 10^{-3} cm^2/s$	Sand blanket(m)	Drain Spacing(m)	Treated depth Ave, (m)	Vacuum (kPa)	Fill (m)	Surcharge (m)	Pumping duration (days)	Settlement Ratio (%)
Guandong Express	14,461	26-90	0.7-2.4	2.60		1.5	30	80	0	4	165	5.7
Xiang Port	480,000	44-64	1.2-1.7	0.8-1.5	0.4	1.3	18	80	0.7		135	8.9
Xiang Port								80	0.7	1	170	12.8
Yaoqiang Airport	145,000	22-48	0.8-1.6	5.00	No	1.3	12	80	0		100	2.1
Nanjing Oil Storage 1	54,000	24-49	0.7-1.4	0.70	0.4	1.0	18	84	1.1		170	6.7
Nanjing Oil Storage 2	27,470	31-57	0.9-1.6	0.70	0.4	0.5	18	80	1.1	0.5	32	8.3
Guangzhou Sewage1	16,445	54-75	1.3-2.0			1.2	15	80	0		90	7.9
Guangzhou Sewage2	2,900	54-75	1.3-2.0			1.2	15	80	0	1	125	7.5
Dalian Bay Alkali	2,025	100-166	2.8-3.6		0.4	1.2	8	80	1.1		56	9.0
Zhuhai Power Station	110,000	40-63	1.2-1.7	0.60	0.4	1.0	20	80	0.9	2	149	9.3
Nanjiang Coal Terminal	24,550	41-60	0.9-1.6	0.70		0.7	20	80			81	7.2
Tianjin Oil Storage	50,000	28-58		2.00	0.3	1.0	20	80	0.4	2	120	4.6
Shenzen Wall	957					1.2	12	80	0	1	120	7.1

c) Japan Vacuum Consolidation with Prefabricated Vertical Drains (PVD)

	Area (m^2)	w_o (%)	$C_c/1+e_o$ (ave.)	Ave. c_v $\times 10^{-3} cm^2/s$	Sand blanket(m)	Drain Spacing(m)	Treated depth Ave, (m)	Vacuum (kPa)	Embankment +surcharge (m)	Pumping duration (days)	Settlement Ratio (%)
Ariake	400	75	0.27	1.50	0.5	0.80	27	60		35	5.0
TohokuRef(2)		194	0.45-0.5	0.81		0.70	10	65		53	8.6
TohokuRef(3)		194	0.45-0.5	0.81		0.70	10	65		52	9.2
Onogawa	7274	120	0.40	1.20	0.5	0.8-1.0	11.6	60		30	6.3
Express Way 337(1)	1036	400-900	0.38	0.58		0.70	20	80	6.0	115	13.0
Express Way 337(2C)	1466	200-400	0.38	0.58		0.70	20	60	13.1	121	21.0
Express Way 337(2H)	2616	200-400	0.38	0.58		0.90	20	60	6.0	104	11.5
Ibaraki	2300	90-750	0.50	2.10		0.80	6.5	80	7.2	47	40.0
Kochi Exp(P45)		700/70	0.20	3.00		1.00	10	70	5.0	120	6.6
Kochi Exp(P65)		700/70	0.35	1.50		1.00	10	70	7.7	127	15.6
Kochi(?)	1800	200/70	0.28	1.50		1.00	10	70	13.6	257	27.8
Niiga Expw	1671	165/70	0.24	1.50	0.5	1.00	8.3	70	8.0	96	16.3
Akita		200	0.45	1.15		0.70	9.5	69	13.0	145	24.8
Hokkaido	4000	260-450				0.7-0.8	20.5	70	9.2	112	12.5
Nagano	1000	470-530		1.27		0.75	8	40		50	6.3
Tohoku WaterTreat	10000	400-600	0.45-0.5			0.70	10	70		48	9.5
Bridge Abutment A	2514	708-175	0.53		0.5	0.80	6.3	70			
Bridge Abutment B	1671	228-103	0.24		0.5	1.00	8.3	70	8.0	96	

pumping duration is also affected by the embankment construction control to ensure its stability. It should be noticed that, distributions of Japan data points in Figs.2 (a, b, c) are used only for demonstration of the trends, but not for comparative purpose due to the fact that values of c_v were used instead of c_h.

Fig.2 (d) presents the performance of the vacuum treatment through plotting settlement ratio (total surface settlement S normalized to treatment depth H) against the combined applied load (approximately estimated as a total from vacuum pressure plus embankment surcharge height). Distribution of data points marked in accordance to average $C_c/1+e_o$ indicates that the settlement ratio ranged between 5-15% largely depending on both combine load and the soil compressibility.

4. VACUUM CONSOLIDATION PRACTICE AND TYPICAL PROJECTS

4.1 Practices in China

In China the vacuum consolidation method has been investigated since 1960s and intensively studied including experimental researches and field trials since early 1980s. During 1982-1996, the method has been applied in total of 31 projects (with total area of 1.6 millions square meters) in the Port of Tianjin only, mainly for improving foundation soils for docks, storage yards, warehouses, sewage treatment facilities, oil tank farms, office buildings and living quarters… and about 20 projects in other areas of China (Liu, 1996). Since 1996 to present, the use of vacuum consolidation is extended to improvement of foundation of expressways, airport runways and seawalls rather than limited for the port structures. By 1996, the total area treated by using the vacuum method was estimated of more than 2 millions m^2 in China. China also extensively employed the method to numerous ground improvement projects in foreign countries.

The East Pier of Xingang Port of Tianjin project conducted by the First Navigational Engineering Bureau of China is the largest vacuum consolidation treatment on reclaimed land of total area of 480,000 m^2 situated over 20m-thick soft clay (Shang et all, 1998). The treatment area was divided into 70 blocks each covering 5,000-30,000m^2 for individual execution of vacuum consolidation. The treatment covers 4m thick very soft hydraulic fill overlaying soft highly compressible peat and organic clays extended to the depth of 20m. The used vacuum consolidation system with PVDs providing vacuum pressure efficiency of 70 % near ground surface (reduced to 50% at larger depth) was successful to bring a total settlement of 1.6-2.3m (induced both by pretreatment and vacuuming) after 135-175 days of pumping. The soil strength increased up to 1700-2300 % at surface and 30-40% at bottom of the treated zone.

4.2 Practices in Europe

In Sweden as well as other Scandinavian countries due to large distribution of very soft sensitive clays, since introduction of vacuum consolidation its applications are mainly in stabilizing the clayey soil foundations of road embankments or buildings. Vacuum consolidation is also popularly employed in other European countries especially France, Germany, Netherlands, Belgium… Utilizing the popular Wick drains, Cofra & Geotechnics Holland BV (Netherlands) conducted various vacuum consolidation projects in Netherlands, including stabilizing very large embankments located near existing buildings to prevent horizontal deformations in the subsoil during embankment construction, expediting large settlement of landfills, dewatering of chemical waste for chemical plants, and expanding its practice to many other developing countries in Asia.

Menard Sol-Traitment – a French company with its oversea branches in America, Europe and Asia developed its own system named Menard Vacuum Consolidation (MVC) in 1989 and since then has gained lots of experiences in design and construction practice through numbers of projects in France and in foreign countries (Cognon et al., 1996). The MVC projects involve road and highway embankments (France, Malaysia), bridge structure (Canada), oil tank farms (France), airport terminal (France), port storage area and warehouse (Germany), wharf (Malaysia), power plant (Thailand) and sewage treatment plants (South Korea) (Masse F. et al., 2001). The Highway A837 (France) is typical domestic project of Menard Sol-Traitment, and its recently completed Kimhae Sewage Treatment Plant project in South Korea has become the worldwide record of successful vacuum consolidation project with the deepest ever treatment depth and highest applied load by that time.

In Kimhae Sewage Treatment Plant project (South Korea, 1995), vacuum consolidation in combination with surcharge and following dynamic compaction have been used successfully to allow construction of the sewage treatment plant on an area of 83,580m^2 located on 25-43m of highly compressible marine clay deposit. The treatment should guarantee a long-term residual settlement of less than 10cm over 10 years under the design load of 33-155 kN/m^2.

The total area had been divided into four sections for treatment separately by employing the MVC system with Menard cylindrical pipes installed at 0.9-1.4m spacing down to the depth of 25-43m. Total of 12 vacuum pumping stations were used (about 7,500m^2/pump). An impervious slurry wall as deep as 9m was constructed to prevent leakage from near surface sandy silt layer. Over 9 months of maintaining 70 kPa vacuum pressure in combination with multi-stage surcharge embankment up to 6.5-15.5m (including 1.5m-thick primary fill applied on the top of 1m-thick sand blanket and beneath airtight membrane), consolidation under the design load has been achieved successfully with average settlement of 4.5m over the area (maximum 6.5m). After completion of vacuum treatment and surcharge removal to a final grade level, dynamic compaction and dynamic inclusion were following to improve the bearing capacity of the fill layer. 20 months after soil improvement, the plant entered its full operation with no residual settlement.

4.3 Practices in Japan

In Japan, although investigation on vacuum consolidation technique had been started quite early since

1960s, however it could have been put in practical applications only since the last two decades when Maruyama-Kougyo Co. Ltd and Hazama Corporation (N&H group) introduced a renewal vacuum consolidation technique called the N&H method. Since then, utilizing newly developed high-tech materials for drains and airtight sheets, the technique has been successfully applied in many domestic projects for ground improvement. Recently, the N&H vacuum consolidation technique has been advanced with utilization of air-water separation vacuum pump system, which ensures a stably high under-sheet vacuum pressure up to 90 kPa during the entire treatment period, allowing shortening the pumping period and thus lowering the cost.

Typical feature of the air-water separation system schemed in Figure 3 is the use of double air-water separation tanks under the airtight membrane. The system works in a manner that the mix of air and water collected by vertical drains, horizontal drains and perforated collector pipes are first led to the supplementary air-water separating tank for being separated, from there the separated water is pumped back by a build-in water pump to the main separating tank through suction hose. Similar separation of the collected air-water mix is also took place in the main tank, where another built-in water pump is responsible for pumping both the just separated water and the water pumped back from the supplementary tank to the vacuum driving system to discharge them outside. The air-water separating tanks are laid beneath the airtight sheet to increase the water discharging efficiency.

Instead of employing the perforated pipe for both collecting and discharging water to vacuum driving system as in previous system, utilization of the build-in water discharge pump in the advanced N&H system helps to overcome the difficulty of maintenance of high vacuum pressure over the entire treatment process when settlement became large and water head dropped down. N&H group had employed this high efficiency vacuum system in several domestic projects.

A typical project was Sanriku Motorway (Tohoku, Japan 2003) - high vacuum consolidation supporting rapid embankment.

In this project, a 12.5m high experimental embankment covering an area of 3750m^2 was constructed on very soft ground consisting of unevenly thick clay and peat layers at the site near Monou Interchange of Sanriku Motorway (Tohoku, Japan). Among various techniques considered, N&H method is the most applicable as it is cost-effective, environmental-friendly and allowing shorten construction time.

The area was divided into 2 blocks for individual treatment. Vacuum consolidation was designed with 70cm thick gravel mat, a system of PVD (type KD-100, 7mm thickness) installed in square grids at 0.8m spacing to the depth of 6-11m depending on the thickness of the soft soil layers. After layout of the air-water separation tanks and perforated collector pipe as well as horizontal board drains (type KD-300) connected to the top of each vertical drain, the area was covered by a special protecting sheet and then an airtight membrane. The membrane edges were sealed off in 2.2m-deep peripheral trench (1.5m into peat layer) and backfilled by the excavated peat.

After layout of vacuum consolidation system and instrumentation, vacuum loading was applied continuously in three stages to 1) improve the initial soil properties, 2) support rapid embankment, and 3) accelerate consolidation after completion of embankment. By utilization of the air water separation system, vacuum pressure beneath the airtight sheet could be attained at record high level of 80-95 kPa and stable during the entire process. Under such high vacuum pressure (about 20-30 kPa higher than designed) the vacuum loading period for

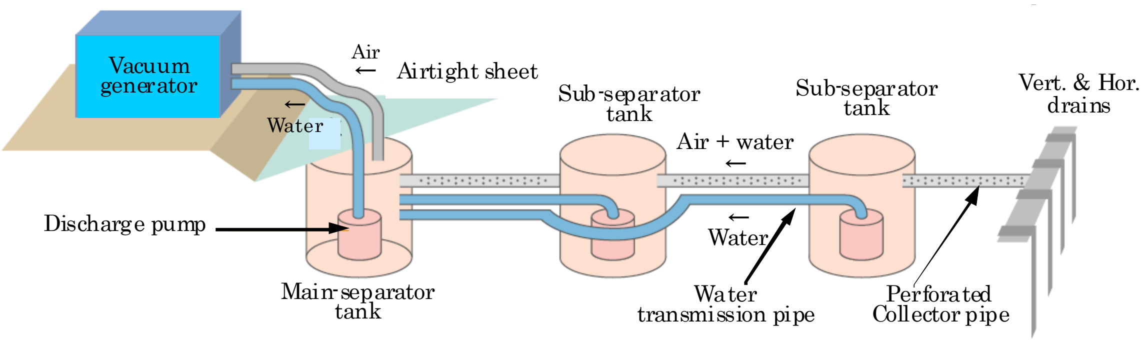


Figure 3　Air water separation vacuum pump system (after Sandanbata et al., 2004)

initial soil improvement could be as short as 30 days, allowing earlier start of embankment, as well as shortening the period of vacuum maintenance after embankment. Consequently the total construction time was reduced and construction cost was lowered. Continuous rapid embankment was executed at an average rate of 13cm/day. The 12.5m height embankment was successfully completed under support of vacuum application for 109 days and maintenance thereafter for 33 more days until complete dissipation of excess pore water pressure. The resulted total settlement by combined vacuum loading and embankment loading was 302 cm in the central area of the embankment.

4.4 Practices in the United States

The US is leading in the field of application of vacuum consolidation for acceleration dewatering and consolidation of hydraulic dredged materials for gaining storage capacity of dumping facilities or reducing the volume of the materials before transportation or treatment.

Sub-aqueous Confined Disposal Facility (CDF) at Newark Bay, New Jersey (U.S. 1997)

The Port of New York and New Jersey constructed a sub-aqueous CDF to contain 1.5 million cubic yards of Category II and Category III contaminated dredged sediments. A study was conducted beforehand to determine the feasibility of using vacuum consolidation to accelerate dewatering of dredged material to gain the capacity of the CDF (Sandiford et al., 1996). In this study, a pit of 2,600,000m^3 in volume was excavated under water at the depth of 20m. An engineering sand layer and horizontal slotted pipes were placed at bottom of the pit before dumping of dredged materials (very soft to fluid mud). Vertical drains (spacing 1.5m) capped at the top were installed down to the bottom sand, then vacuum pressure was applied from bottom by a submerged vacuum pump. The system is sealed by the top soil layer to prevent short circuiting to the bay above. With vacuum application over 2 years, settlement of 8.2m was recorded inducing an increase of 855,000m^3 in capacity of the CDF. Compared to the other method, vacuum consolidation provides the most capacity and at least cost (US$ 9.5/m^3).

5. Conclusions

Numbers of published documents and research papers on vacuum consolidation practice from different countries in the world with typical vacuum consolidation system configurations and design criteria are reviewed.

Actual design parameters from various actual projects of soft ground improvement conducted in Japan, China, France and other countries were sited or interpreted from published documents or papers, then tabulated and plotted in graphs for comparison.

Furthermore, typical vacuum consolidation systems developed for accelerated dewatering fluid-like materials including hydraulic dredged fill are also reviewed with typical example on system with vertical drains or systems with lateral drains.

Finally, the paper summarizes application practices in leading countries with typical case histories for illustration of effectiveness of the vacuum consolidation method. And the new advanced system (air-water separation N&H Method) is introduced.

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真空圧密工法　ー世界各国の施工事例と日本における最新技術

ダム　ティー　キム　ローン，三反畑勇，木村　誠

真空圧密工法は，軟弱な粘性土地盤に真空圧（負圧）を作用させて間隙水圧を低下させることによって，全応力を変化させずに有効応力を増加させる地盤改良技術である。近年の設計・施工技術の向上によって，効率的で経済的な軟弱地盤対策工法として認められ，施工実績が増加している。また，泥土の脱水・圧密促進といった分野にも応用範囲を拡げている。真空圧密工法はこれまでに世界各国で多くの施工事例があり，施工実績の蓄積が技術の進歩に大いに貢献してきた。本文では，それらの実績から有用な情報を得るため，真空圧密工法の多様なシステムをその特徴及び設計・施工面から整理，比較するとともに，日本国内における最新の開発技術について紹介する。