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Successful Application of Menard Vacuum Consolidation Method to Nakdong River Soft Clay in Kimhae, South Korea

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ABSTRACT : The Vacuum Consolidation Method utilizes the atmospheric pressure to consolidate soft saturated sediments by similar principles as those used in surcharge preloading by vertical drains. The surcharge is applied by vacuum load (0.7 to 0.8 bars) equivalent to a 4 m embankment. The vacuum preload is isotropic, independent of depth and leads to an immediate decrease of pore water pressure. As the deviatoric tensor of stress is not modified, it allows the rapid construction of embankment without risk of failure. Main applications of the Menard Vacuum Consolidation™ Method are in the construction of highways, airport runways. A new field of application has been developed for the first time in South Korea, for the construction of a new sewage treatment plant.

1 . INTRODUCTION :

fig1: The Nakdong River plain, Pusan, South Korea

This document presents the results of soil improvement by Menard Vacuum Consolidation™ method performed on Kimhae Sewage Treatment Jobsite, South Korea .

The site is located in the plain of Kimhae , West of Pusan city, South Korea. The existing sewage treatment facilities for the city of Kimhae, with large new apartment complex areas having been built these recent years, revealed to be too old and the treatment capacity too small for the current needs.

As a result, it has been decided to build a new sewage treatment plant with a capacity assuring efficient treatment of the sewage water for a city of more than 500 000 citizens.

Along the banks of the Nak Dong River, the new 160 000 m^2 sewage treatment site is located on highly compressible clay with depth varying from 25 to 43 m resulting of the past marine deposit in this 20km x 20km plain.

Instead of using the traditional method of piling widely spread in South Korea, an alternative using Menard Vacuum Consolidation™ has been proposed to achieve a 100% primary consolidation under the loads of buildings and fill and 10 years of secondary settlement within a limited consolidation period.

Although Menard Vacuum Consolidation™ had been successfully applied in the past to road and embankment projects in France, it had never been seriously investigated as an alternative to piles and/or conventional pre-loading. The Kimhae project is the first of its kind for such extreme soil conditions and structure loads and more important, for such severe specifications. It has led to the development of new geotechnical tools and calculation methods at design stage as well as during monitoring period, mainly based on settlement and void ratio analysis, in order to successfully achieve the requirements of the contract.

2 . INITIAL SOIL CONDITIONS

The Nakdong river delta area, south east part of the Korean peninsula, has been the theatre of deposit of large thickness of alluvial sediments up to 45 m deep. The characteristics of this very soft clay are rather homogeneous through the thickness of the compressible layer. On site, the depth of bottom hard layer (sand and weathered rock) varies from 25 to 43m. An extensive preliminary soil investigation including SPT, CPT, in-situ vane tests and laboratory tests allowed to give a detailed picture of the subsoil conditions before starting the design of the soil improvement treatment. The modelization of the subsoil for design purpose is summarized as below :

Layer	type	h	γ (t/m3)	eo	Cc	Cv (m2/y)
Layer 1	ML	5 to 10m	1.58	2.012	0.91	1.32
Layer 2	CH	15 to 30m	1.58	2.012	1.21	1.32
Layer 3	CL to SM	4m	1.58	0.98	0.20	1.32

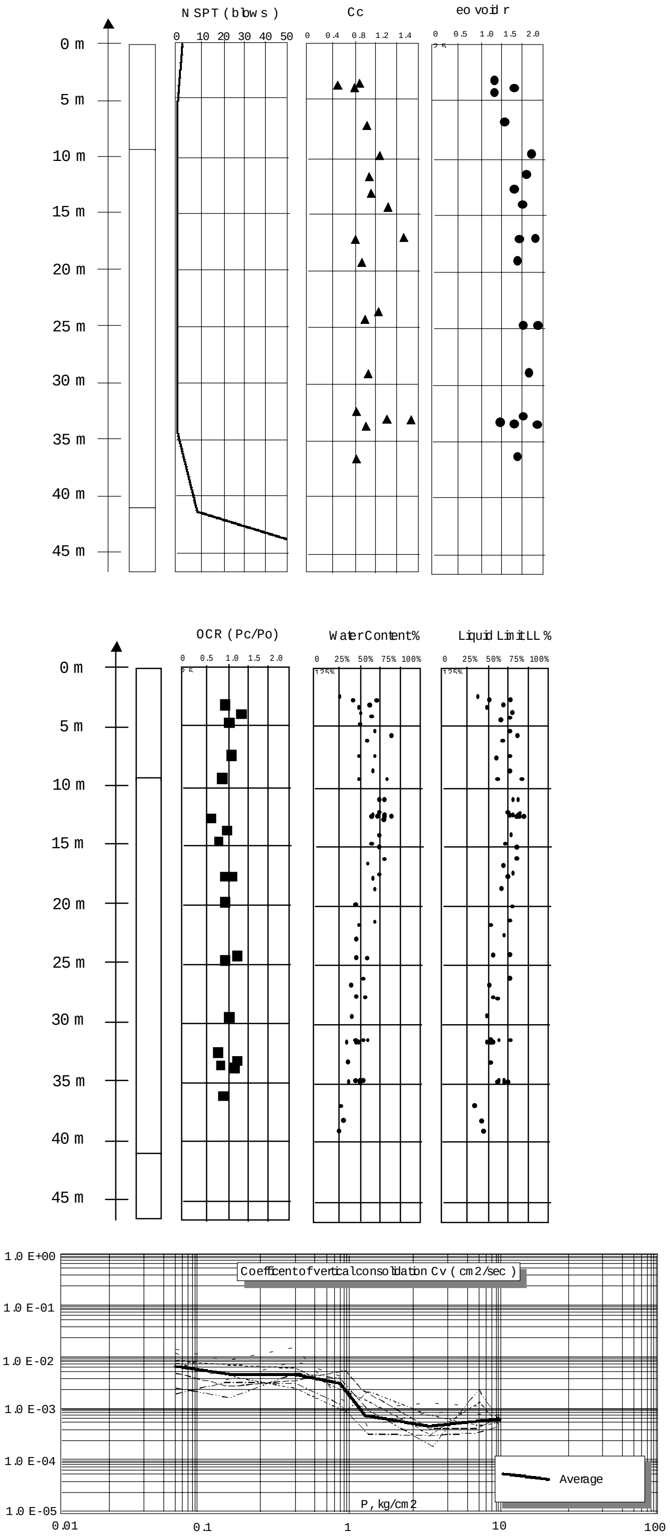


Fig 2 : preliminary soil investigation results

3 . CONCEPTUAL DESIGN

Menard Vacuum Consolidation™ method provides an alternative to classical preloading by Surcharge. The classical preloading method increases the effective stress in the soil mass by increasing the total stress of the preload weight whereas Vacuum Consolidation preloads the entire soil mass by reducing the pore pressure while maintaining an unchanged total stress. Atmospheric pressure Pa is generally not considered on soil engineering calculation of total stresses as Pa is rarely a varying parameter in classical calculations. In order to fully understand the concept of vacuum consolidation, it is necessary to re-introduce Pa in the equations.

For classical preloading h :

$\sigma_T = \gamma.z + \gamma_f.h + P_a = \sigma_t + Pa$ $\quad u_T = \gamma_w.z + Pa = u_t + Pa$

As a result, $\sigma' = \sigma_T - u_T = s_t - u_t = \gamma'.z + \gamma_f.h$

For vacuum consolidation (assuming an efficiency of 80% of vacuum) :

$\sigma_T = \gamma.z + Pa$ and $u_T = \gamma_w.z + Pa - 0.8\ Pa = \gamma_w.z + 0.2\ Pa$

And $\sigma' = \sigma_T - \upsilon_T = \gamma'z + Pa - 0.2Pa = \gamma'.z + 0.8Pa$

As a result, as far as load is concerned, vacuum effect is equivalent to a surcharge height of about h = 4m.

If we consider stress paths, for classical preloading, on the (p',q') diagram, the stress path follows the Skempton AB curve with a risk of slope failure if the point B reaches the failure line. Then, the consolidation takes place according to an horizontal line BC to reach the point C at end of consolidation. In the oedometer case, as p'/q' remains constant, the stress path follows the Ko line till point D. C and D have the same σ1'.

As far as vacuum consolidation is concerned, the vaccum load being the same in all directions (isotropic stress), we have $\Delta\sigma'_v = \Delta\sigma'_h$ and the stress path is an horizontal line AE.

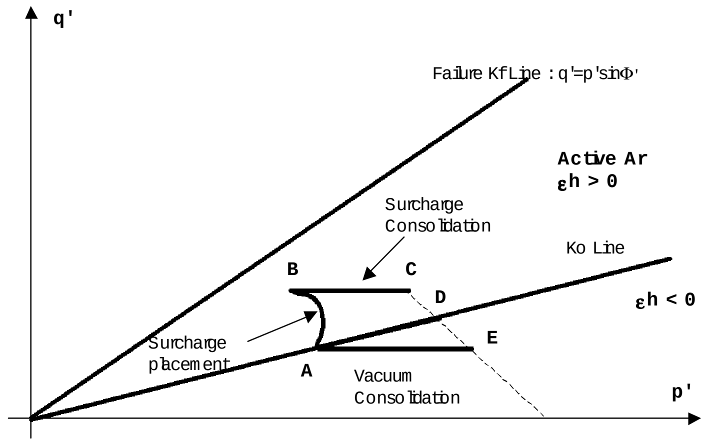
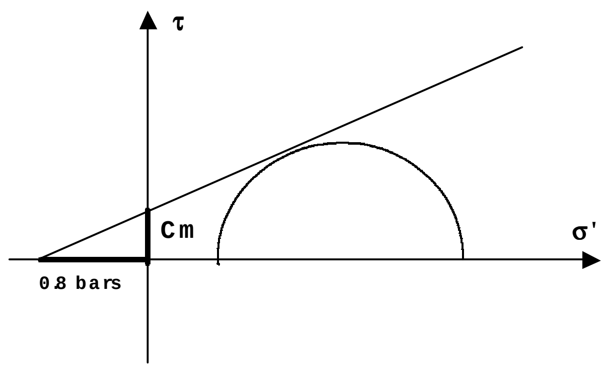


Fig 3 : comparison classical Preloading / Vacuum in (p',q') diagram

As a result, due to the isotropic increase of effective stress, there is no risk of slope failure with the Menard Vacuum Consolidation™ technology. The safety factor, stresses following the AE line, increases with consolidation. In addition to that, the vacuum increasing isotropically the stresses under the membrane, the Mohr circles in the fill shall move to the right and it creates an apparent artificial cohesion in the fill C_m=0.8 bar x tan ϕ. This is the same that happens in vacuum-packed coffee .



As a result, in the case of combination of vacuum with classical preloading, safety factor is improved.

4 . APPLICATION TO KIMHAE SEWAGE TREATMENT PLANT PROJECT

The treatment area was 160 000 m^2 divided into two phases of 80 000 m^2 each. The typical loads ranged from 3 to 15 t/m^2 with foundation depth varying from 0 to –7m from final ground elevation. Initial ground level was close to 0 with a final elevation of the plant set at +3.00 m. As the sewage treatment plant had been designed for a gravitary process (the flow of the sewage waters inside the plant is based on the gradient of pressure due to gravity only, with no pumping facilities throughout the process). As a result, criteria on total and differential settlements were extremely severe.

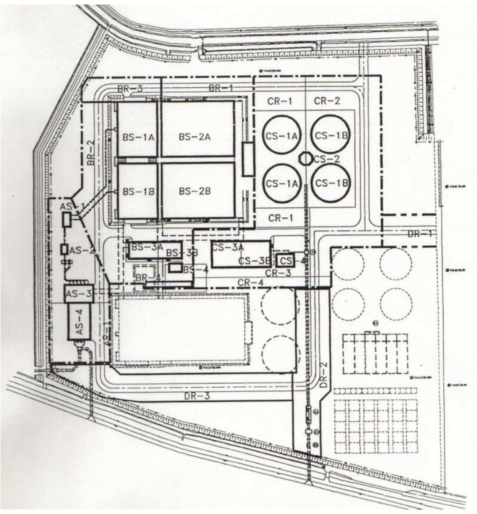


Fig 5 : General Layout plan of the Kimhae Sewage treatment plant

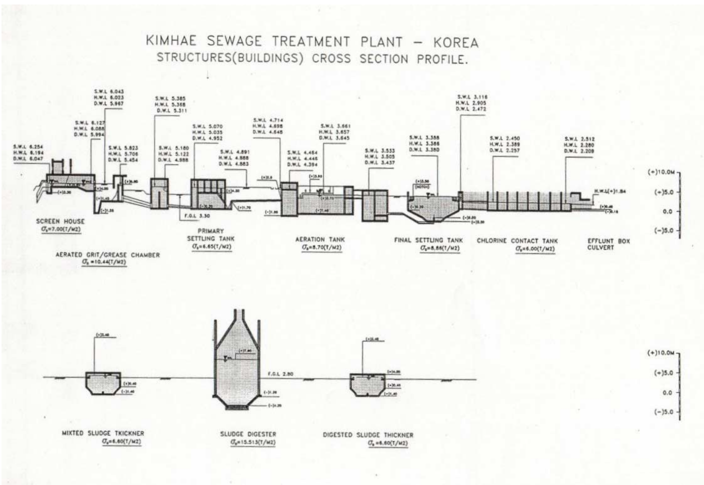


Fig 6 : Structure Cross section Profile

The initial design based on the preliminary soil investigation results had led to predicted settlement ranging from 3 to 5.5 m depending on the loads and the areas for a final guarantee of 10 cm of allowable settlement over 10 years under the combined load of the fill and the buildings. Fig 7 illustrates a typical cross section of the Menard Vacuum consolidation™ method on Kimhae STP jobsite. The typical working sequence is as follows :

(1) Placing a woven geotextile (10t/m^2) and a sand blanket (1m thick) to provide a suitable working platform as well as an efficient draining layer.

(2) Installation of Menard Cylindrical transmission pipes ($\Phi = 50$ mm) (grid ranging from 0.9x0.9 to 1.7x1.7).

(3) Installation and connexion of horizontal drainage network transversally and longitudinally towards pumping stations

(4) Performance of impervious slurry wall to create a tight closed box and securing isotropic load

(5) Geotechnical instrumentation : 48 control points including 1 settlement plate, 1 settlement sphere, 1 Vacuum Pressure Gage, 1 Multidepth settlement gage and 1 Piezometers. Each control point is connected to an acquisition station linked to site office by internet.

(6) Excavation of peripheral trenches and sealing with bentonite and polyacrylate.

(7) Placement of primary fill (h=1.5m) above membrane.

(8) Lay-out and welding of PVC membrane. Installation of pumping stations. Start of Vacuum pumping operation (12 pumping units).

(9) Placement of fill surcharge on top of membrane for settlement compensation, reaching the final ground level and acceleration of settlement.

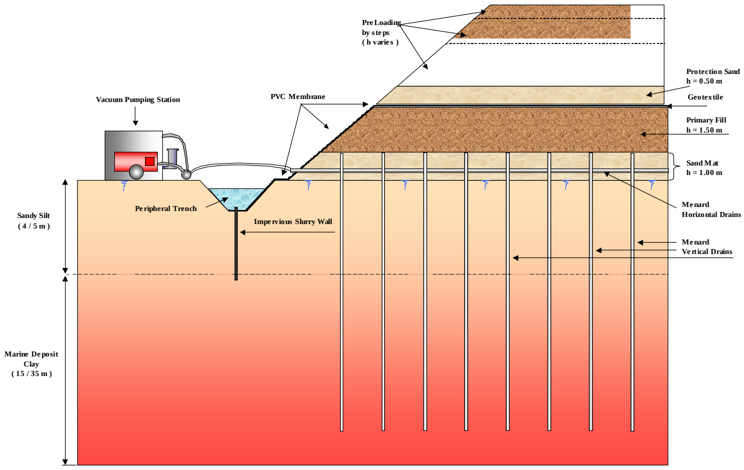


Fig 7 : Principle of Menard Vacuum Consolidation™

5 . CALCULATION METHOD - MONITORING

Because the performance criteria were extremely severe, a calculation procedure had been developed to determine the moment when Vacuum operation could be safely stopped. As it was not possible to rely only on the pore pressure analysis, it has been decided to perform design and back-analysis calculations based on a void ratio target to meet the guarantee criteria. It has to be kept in mind that the guarantee of 10cm over 10 years represents a mere 2% of the total maximum settlement of 6.5m recorded during the course of the Vacuum. This is far beyond the accuracy of soil mechanics theories !!!

As a consequence, the concept of void ratio target and settlement target had to be introduced for each layer.

At the design stage, for each area, a settlement target has been calculated with initial soil parameters. This settlement target based on target void ratio for each layer is the minimum settlement to achieve in order to meet the settlement criteria. For the determination of this settlement target, a loop calculation has to be performed :

$$\Delta\sigma'(z) = \gamma H_{fill} + \sigma_o + \gamma'\Delta H_{primarysettlement}$$

$$\Delta H_{primarysettlement} = \frac{C_c}{1+e_o}.H.\log(\frac{\sigma_o + \Delta\sigma'(z)}{\sigma_o})$$

100% of primary settlement.

Then secondary settlement is determined separately depending the aging of the clay that is required by the contract.

Nevertheless, as preliminary soil parameters do not reflect exactly the actual behavior of the clay on site, it is necessary to constantly re-adjust the value of soil parameters and settlement targets : theory is calibrated through actual site monitoring results and back-analysis of the monitoring datas as shown in fig. 8 :

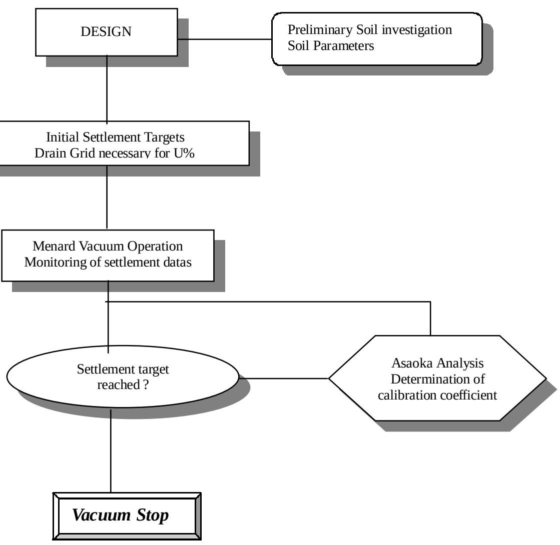


Fig 8 : Flowchart of design and Backanalysis process

The data obtained from site control points are automatically stocked in an acquisition station located on site . Daily, the data are transferred through internet on a server connected to the engineering department. Each serie of data is saved in a specific file for further analysis.

The main tool used for back-analysis is the Asaoka method. Once the Asoaka settlement is calculated at time t for the actual load on site, it is possible to compare ΔH_{asaoka} with the value obtained by the consolidation theory equations ΔH_{theory}. At that point, a calibration coefficient β is introduced to take into account the discrepancy between actual results (ΔH_{asaoka}) and the theoretical approach (ΔH_{theory}). It can be easily shown that :

$$\beta = \frac{\Delta H_{asaoka}}{\Delta H_{theory}} = \frac{(\frac{Cc}{1+e_o})_{actual}}{(\frac{Cc}{1+e_o})_{soilinvestigation}}$$

Once β is determined for each control point, settlement targets are re-calculated for each layer using the following formula (primary settlement):

$$\Delta H_p = \beta\frac{C_c}{1+e_o}\log(\frac{\sigma_o + \Delta\sigma'}{\sigma_o})$$

Settlement targets are then compared to settlement monitoring results as shown fig 8.

6 . RESULTS OF VACUUM CONSOLIDATION™

After 7 to 9 months of operation, vacuum pumping was successfully stopped on all areas. The back-analysis calculations have led to values of b ranging from 0.861 to 0.999 with an average value of 0.915 . Which means that we have obtained 91% of the theoretical decrease in void ratio needed to guarantee 10 cm of residual settlement over 10 years.

	Minimum	Maximum	Average
Pumping period	7 months	9 months	8.5 months
Surcharge height	8m	17m	10m
Settlement	3.55 m	6.45 m	4.55 m
Calibration b	0.861	0.999	0.915

Fig 9 : maximum surcharge height : 17m

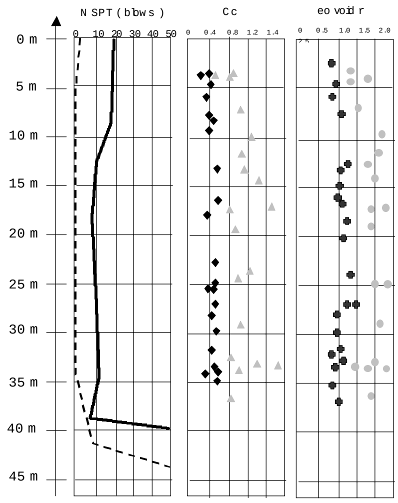


Fig 10 : Soil improvement comparative results

The average values are summarized below (results in the clay layer) :

	Before	After
SPT N	0	7 to 10
eo	2.215	1.55
Cc	1.21	0.54
W%	85-90%	40-45%

OCR	0.980	2.42

The success of the vacuum method has been validated by full-load tests immediately after end of pumping (Surcharge load test) and when the plant in operation (Water test). Both load tests revealed successful with no residual settlement recorded after end of vacuum and a settlement at water test under 3 cm .

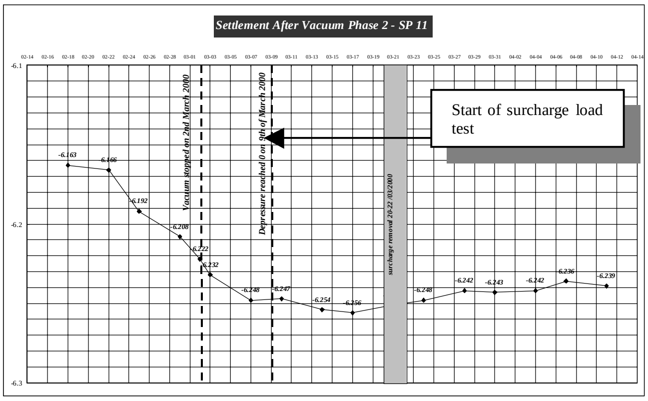


Fig 11 : Settlement results at surcharge full-load test

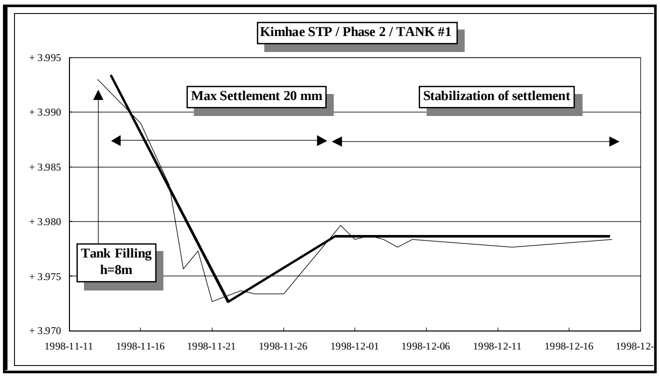


Fig 12 : Settlement results at Water test

The plant has been operating since January 2000 for the first phase of the project. The second phase is currently under construction with water tests scheduled for year 2001

7 . CONCLUSION

On Kimhae Sewage Treatment Plant project, Menard Vacuum Consolidation™ has revealed an effective method (technically and economically) to improve, combined with classical pre-loading, highly compressible clay layer with thickness over 35m. Already acclaimed in France for road and embankment construction, the success of Kimhae STP project has opened a new era of development for Vacuum consolidation for soil improvement under concrete structures with severe settlement criteria as an economical and technically viable alternative to piles.

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