A Vacuum Consolidation Method Application Case for Improving Dredging Slurry

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ABSTRACT: An industrial estate near a seaport located at north China is planned to be built on a reclamation land with dredging slurry. An extremely soft slurry layer with thickness 7.0 ~ 8.0 m are formed on the surface and an original soft silty clay layer with thickness 5.0 ~ 6.0 m is below the slurry layer. Neither common ground improvement machines, nor human being is able to enter the reclamation land due to extremely high water content and low bearing capacity which result the biggest challenge for ground improvement construction in this case. Vacuum consolidation method is employed to improve dredging slurry and original soft silty clay layer, which is started about one month after dredging construction. The biggest challenge part of ground improvement construction is overcome by establishing a working platform consisted of woven geotextile, bamboo raft and hydraulic backfilled sand cushion. Surface settlement plate, extensometer, vacuum dial, piezometer and inclinometer are employed for monitoring. Load plate test and cone penetration test are used for evaluating ground improvement performance. All monitoring data and performance test result are presented and discussed in this paper.

Keywords: Dredging slurry, Reclamation land, Vacuum Consolidation Method.

1 INTRODUCTION

Vacuum consolidation method (also known as vacuum preloading method) was initially proposed by Kjellman at 1952 [1] and was worked out by the Royal Swedish Geotechnical Institute as a method for improving fine grain soil. This method utilizes atmosphere pressure as a temporary surcharge for improving fine grain soft soil. However, in the several following decades, this method was not widely applied due to the difficulties for maintaining effective vacuum pressure. With the improvement of methodology and technology of producing better vertical drains and airtight sheets, this method was introduced and applied in many countries. Now, this method is widely applied in worldwide, especially in Europe, U.S.A, China, Japan and several other Asian countries.

Vacuum consolidation method was introduced into China in 1960's but was successfully applied until early 1980's. Since then, this method has been employed in hundreds of projects in China for ground improvement. Furthermore, the development of construction machinery and technique allowed the method been applied in various soil conditions or site conditions [2][3][4][5]. This method was introduced into Indonesia at 2007 and has been successfully applied in several projects under difficult site condition[6].

Some advanced construction methods have been developed during those successfully applications. These accumulated advanced construction method, monitoring data and experience help us to better understand the advantages and risks of this method and to use this method more proper. Furthermore, the advanced vacuum consolidation methods tends to enlarge the range of soil material which human being can utilize for reclamation.

2 VACUUM CONSOLIDATION SYSTEM

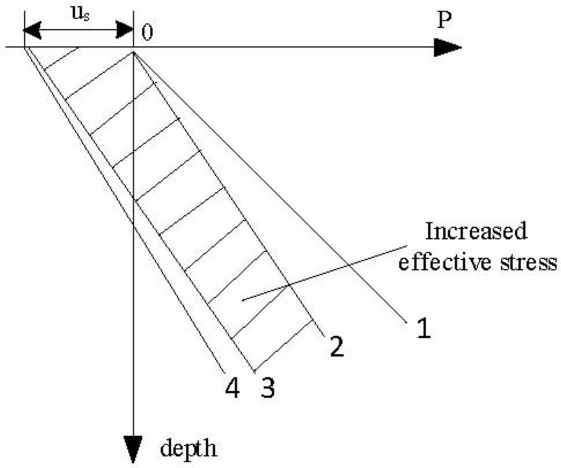
The basic idea of vacuum consolidation method is applying a vacuum suction into an isolated soil mass to reduce the atmosphere pressure and pore water pressure in the soil, resulting soil consolidation and effective stress enhance without change the total stress [7][8][9]. The principle is described as Figure 1.

Basically, the whole vacuum consolidation system consists of drainage system, isolation system and vacuum pumps. Once generated in vacuum pumps, vacuum suction rapidly spreads into soils along drainage system, reducing atmosphere and pore water pressure and forming pressure difference between vertical drains and pore water in soils. This pressure difference causes the pore water flows toward vertical drain which means soil consolidation happens. Vacuum suction keeps taking out water and air, accelerating soil consolidation.

Drainage system is an interconnected network of PVD, horizontal filter pipes and sand layer, forming a complete path for spreading of vacuum suction and water flow.

Isolation system is used to cutoff leakage of water & air below it. It consists of geomembrane, the soft clay itself and cutoff wall if necessary.

The sketch of general vacuum system is showed as Figure 2.



Note: 1-Total stress line, 2-initial water pressure line, 3-water pressure line after vacuum applied, 4-water pressure line if without head lose

Figure 1. Principle of Vacuum consolidation.

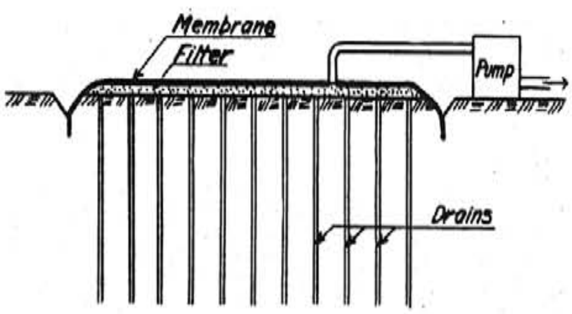


Figure 2. Sketch of general vacuum system.

In the lateral direction, vacuum suction exerts an inward force into the subsoil which is totally different with surcharge preloading where an outward force is exerted. As a result, in most cases, the sliding failure mechanism could be partly or totally eliminated when applying vacuum consolidation method. This is a distinguished advantage when conducting ground improvement on very soft ground or beside existing buildings or infrastructures.

In conventional vacuum consolidation method, sand layer is an important part for the whole system which provides horizontal drainage function, as well as working platform in some cases. Conventional vacuum consolidation method has been proved its good performance in improving soft clay. However, it is a big challenge to apply this method to improve dredging slurry material due to the extremely high water content & nearly zero bearing capacity condition. Some advanced vacuum consolidation construction method and a successful case is presented in the following articles.

3 AN ADVANCED VACUUM CONSOLIDATION FOR IMPROVING DREDGING SLURRY CASE

3.1 *Project introduction*

A planned industry & logistic estate is located in Zhuanghe port of DaLian city in northeast China (shown as Figure 3). The master plan of Zhuanghe industry & logistic estate is showed in Figure 4.

Considering the sand resource is quite far and expensive, the project owner decided to utilize dredging material for reclamation due to soil volume balance and cost control purpose. The whole estate was divided into two development phase: phase #1 cover 71 hectares and phase #2 cover 93 hectares.

Figure 3. Project location of Dalian Zhuanghe port.

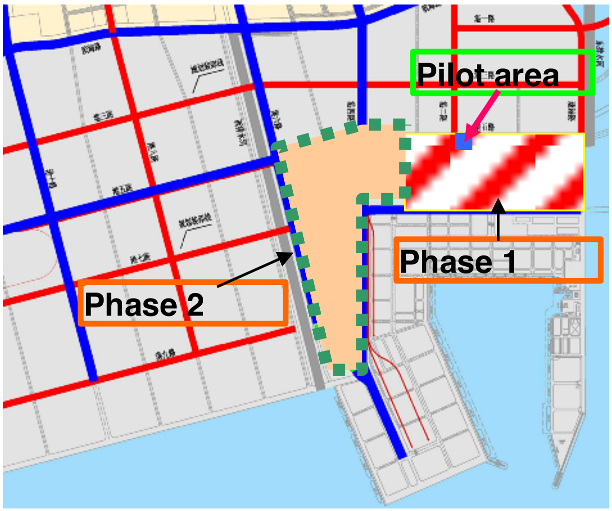


Figure 4. Master plan of Dalian Zhuanghe port.

3.2 *Soil conditions*

Soil investigation report and pre-CPT test result indicated that the soil material in seabed is mostly silty clay or clayey silt. There are two soft soil layers with very soft to soft status which need to be improved:

Layer 1 – Dredging slurry, clayey silt or silty clay, very soft, flowable to soft plastic, average depth 7.0 ~ 8.0 m, with extremely high initial water content, nearly zero bearing capacity.

Layer 2 – Clayey silt or silty clay, soft to soft plastic, average thickness 5.0 ~ 6.0 m, initial water content 41.6%.

Layer 3 – Silty clay, medium to hard stiff.

The typical cross section of subsoil layers is showed as Figure 5. Moreover, some lens sand layers were founded at part of the improvement boundary which is showed in Figure 6.

Vacuum consolidation method was employed to improve the dredging slurry and soft clayey silt or silty clay layer. Total quantity of improved area is 71 hectares for phase #1 and 93 hectares for phase #2.

3.3 *Technical requirement*

a) Surface bearing capacity ⩾ 100 kPa after leveling & settlement compensation soil backfilled using red clay.
b) Bearing capacity at any point along 13 m depth not less then 50 kPa.
c) Long term settlement under 50 kPa working load is less then 30 cm.

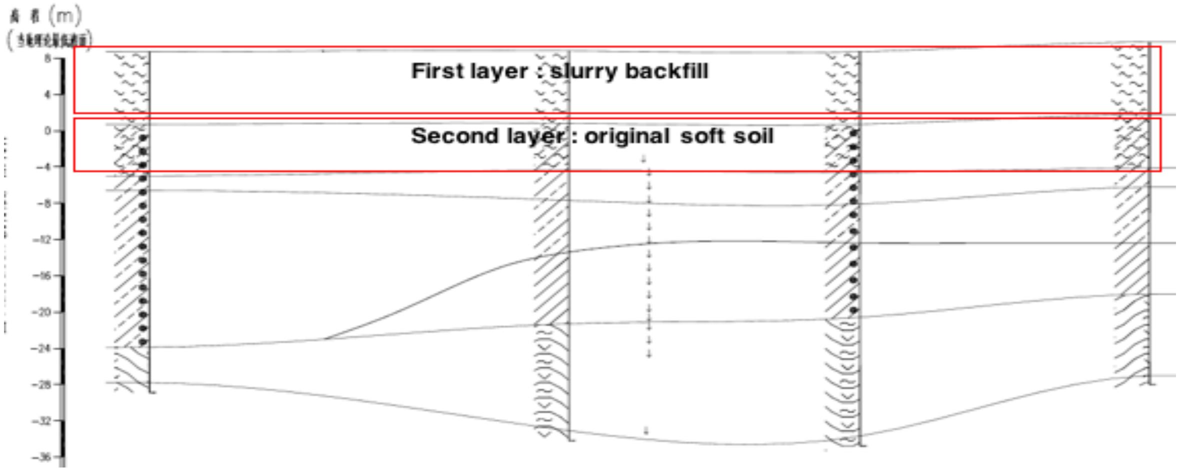


Figure 5. Typical cross section of subsoil layers.

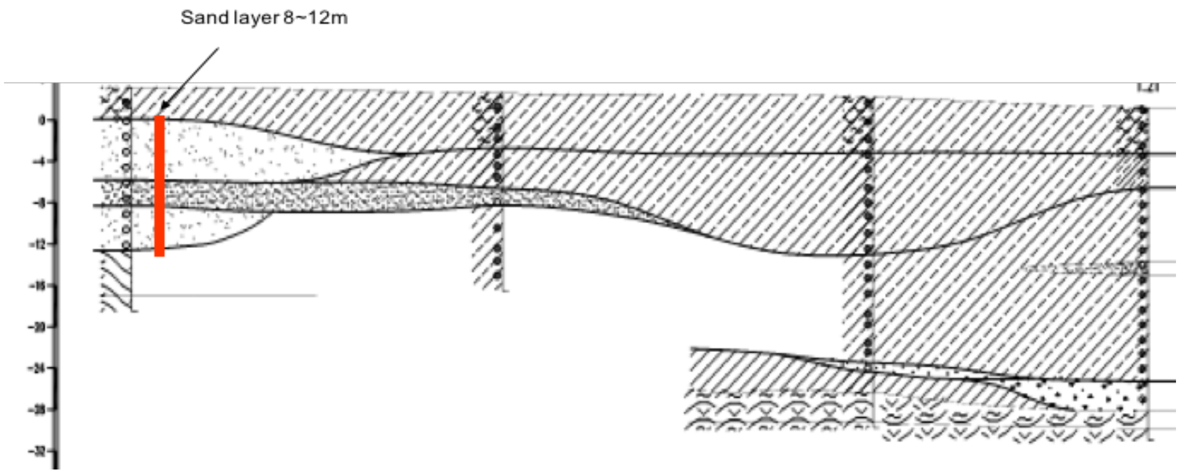


Figure 6. Lens sand layer at part of the boundary.

3.4 *Construction process*

The whole project site is divided into several block with every block cover 30 ~ 40 hectares. Dikes were built along the boundary or interface of the blocks by backfilling compacted rocks and soil. Dredging slurry material was backfilled by hydraulic filling method. The construction process is showed in Figure 7.

a) Dike construction.

b) Dredging slurry backfilling.

c) Site situation after backfilling.

Figure 7. Construction photos of dike construction and dredging slurry backfilling.

The biggest challenge to apply vacuum consolidation method in Dalian Zhuanghe project is how to establish a working platform above dredging slurry. A combination of woven geotextile, bamboo grid and hydraulic sand filling was developed to build working platform and horizontal drainage for application of vacuum consolidation method. The construction steps are described as:

1) The woven geotextile was sewn as big sheets with size 30 * 60 m before spreading.
2) Labors lower their body on knee and carefully spread geotextile from block boundary inward.
3) Bamboos were installed in grid pattern, with grid size 0.25 ~ 1.0 m.
4) Spread another layer of woven geotextile above bamboo grid.
5) Backfill 0.4 m thickness sand by hydraulic filling method.

The construction process of working platform are described as Figure 8.

a) Spreading woven geotextile above slurry.

b) Installing bamboo grid.

c) Spreading another layer geotextile above bamboo grid.

d) Backfill 0.4 m thickness sand by hydraulic filling method.

e) Site condition after establishing working platform.

Figure 8. Construction photos of working platform.

After the working platform is ready, the standard procedure of vacuum consolidation construction shall be performed:

1) Install vertical drains (PVD) using light PVD installation machines.
2) Install horizontal pipes.
3) Install non-geotextile and geomembrane.
4) Install vacuum pumps and running until the average consolidation degree reach 90%.

The construction photos of vacuum consolidation method are showed as Figure 9.

a) PVD installation.

b) Horizontal pipes installation.

c) Non-woven geotextile installation.

d) Geomembrane installation.

e) Vacuum pumps installation & running.

Figure 9. Construction photos of vacuum consolidation method.

3.5 *Monitoring & Inspection*

As an invisible water & soil behavior which occurs underground, process monitoring is very important for quality control. To ensure the improvement quality, several monitoring measures were employed to monitor the vacuum status and consolidation progress:

a) Vacuum dial: vacuum consolidation method is sensitive to any leakage of air and water. Vacuum dial will present the status of vacuum pressure and expose any leakage.
b) Ground surface settlement: it will indicate the total settlement during consolidation process and the monitoring data could be used to derive average consolidation degree.
c) Piezometer: it will indicate the vacuum status.
d) Extensometer: it will indicate the settlement or improvement effect of deep layer soft soil.
e) Inclinometer: it could indicate the lateral displacement of subsoil and sometimes could be used to monitor the effect on existed buildings or structures.

Cone penetration test: pre-CPT and post-CPT shall be performed before and after improvement to indicate the improvement effect. The layout of monitoring items in the pilot test area is shown as Figure 10.

The monitoring data, shown in Figure 11 and Table 1, indicated that:

1) Ground surface settlement could reach more than 1.0 m and it varies in a relative large range in different location. Author interpreted this phenomenon is due to uneven sediment behavior during hydraulic backfilling. The location with smaller size soil particles shall result relatively higher water content and bigger settlement.
2) Vacuum dial and pore water pressure data indicated that vacuum pressure is stably maintained and well spread into deep soil layer.
3) Extensometer monitoring data indicated the deep subsoil settlement due to compression activity under vacuum pressure.

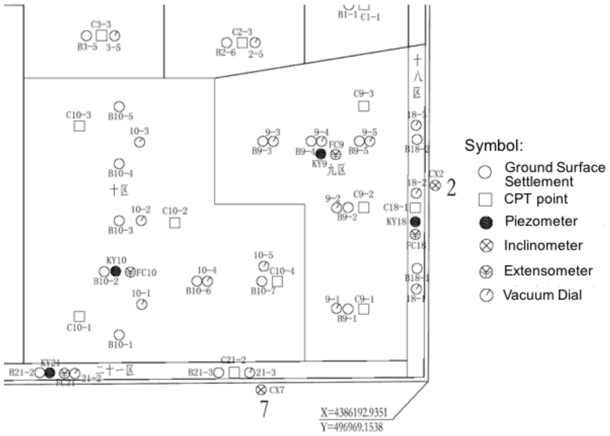
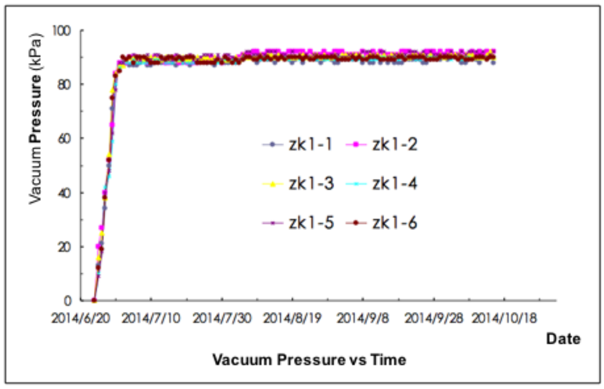
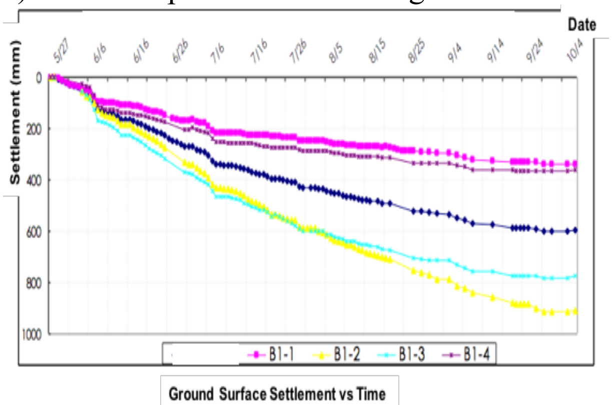


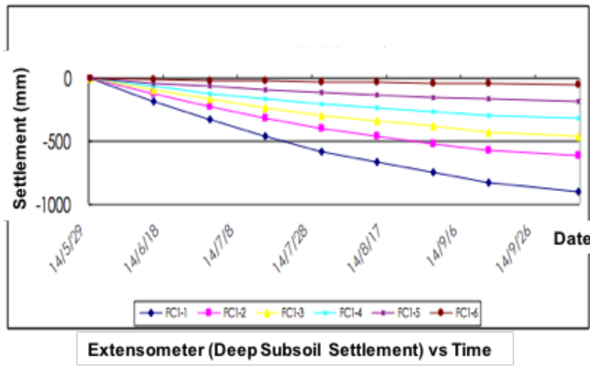
Figure 10. Layout of monitoring items in pilot test area.



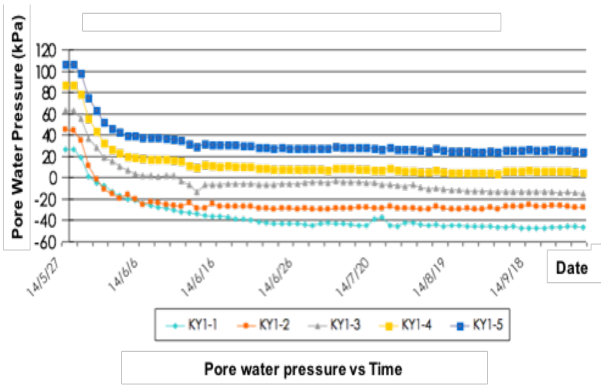
a) Vacuum pressure monitoring data



b) Ground surface settlement monitoring data



c) Extensometer monitoring data



d) Pore water pressure monitoring data
Figure 11. Monitoring data of pilot test area.

Table 1. Ground Settlement Summary.

Subzone	Total Settlement (mm)	Average Settlement Rate (mm/d)
B 1-2	908	4.45
B 2-5	1489	8.95
B 3-5	1174	6.82
B 10-3	752	5.44
B 12-4	1197	9.76

Plate load test and cone penetration test are employed to inspect the improvement result. Plate load test and CPT result are shown in Table 2 and Table 3 respectively.

Table 2. Summary of plate load tests.

No.	½ of max load		Max Load		Allowable bearing capacity (kPa)
	Load (kPa)	Settlement(mm)	Load (kPa)	Settlement(mm)	
J1	100	3.17	200	7.65	⩾100
J2	100	4.21	200	10.36	⩾100
J3	100	2.34	200	5.62	⩾100
J4	100	2.30	200	5.34	⩾100
J5	100	4.11	200	8.12	⩾100

Table 3. Comparison of CPT qc value before and after vacuum consolidation improvement.

Soil Layer	Before (Mpa)	After (Mpa)	Increment (%)
(1) Sand platform	1.76	4.63	163
(2) Slurry backfill & soft clay	0.25	0.67	168
(3) Medium to hard stiff silty clay	0.91	1.03	13

Furthermore, besides the above inspection tests, several site pit is excavated to indicted the slurry status after improvement (shown as Figure 12).

a) Before improvement

b) After improvement
Figure 12. Comparison of slurry status before and after vacuum consolidation improvement.

4 DISCUSSION & CONCLUSION

So far, numbers of books, papers, reports and documents about mechanism, methodology and practice of vacuum consolidation method have been published in different countries. A lot of experimental or monitoring data has been presented among these literals. All these efforts or achievement provide a better understanding and quality control of this technique, as well as technical transfer.

In conventional vacuum consolidation method, sand layer is an important part for the whole system which provides horizontal drainage function, as well as working platform in some cases. Conventional vacuum consolidation method has been proved its good performance in improving soft clay. However, it is a big challenge to apply this method to improve dredging slurry material due to the extremely high water content & nearly zero bearing capacity condition.

In a planned Dalian Zhuanghe port industry & logistic estate project, dredging slurry material was used for reclamation and vacuum consolidation method is employed to improve dredging slurry and soft clay with some advance construction method. The biggest challenge to apply vacuum consolidation method above dredging slurry is how to establish a working platform above the slurry. A combination of woven geotextile, bamboo grid and hydraulic sand filling was developed to build working platform and horizontal drainage for the following vacuum consolidation construction.

As an invisible water & soil behavior which occurs underground, process monitoring is very important for quality control. Several effective monitoring measures were employed to monitor consolidation process: vacuum pressure, daily ground surface settlement, sub soil settlement by extensometer, pore water pressure and lateral displacement by inclinometer. Furthermore, plate load test and cone penetration test are used for improvement effect inspection. Monitoring data and inspection result proves the dredging slurry and soft clay have been significantly improved by the advanced vacuum consolidation method.

With respect to the fact that Indonesia economic keeps growing up, investment activities, city expanding, industrial development and infrastructure facilities require more and more land resource. The conflict between rapid development and limited good land resource requires people to utilize the land with difficult conditions or create land by reclamation.

In most reclamation cases, rock, gravel, sand or red clay are the common material for backfill. However, material mentioned above are limited resource. All limited resource will tend to be more and more expensive along the fast development.

In some content, dredging slurry is believed to be unsuitable material for reclamation in the past. The advanced vacuum consolidation method create more possibility to utilize dredging slurry for reclamation which shall bring benefit in overall cost and environment protection.

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