China Ground Improvement Scan Tour Report

Sponsored by the ASCE Geo-Institute

Organized by the ASCE Geo-Institute Soil Improvement Committee

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1. INTRODUCTION

1.1 Background

During the last four decades, China has made significant improvement in various sectors of its infrastructure: high-speed railways, long-span and cross-sea bridges, large dams, long and large-diameter tunnels, land reclamation, etc. Many soil improvement technologies have been successfully adopted for these projects. More importantly many new soil improvement technologies have been developed, improved, and successfully implemented on major projects.

Due to language barriers, most of the technologies implemented have not been introduced to the international community. The Geo-Institute (G-I) Soil Improvement Committee successfully organized a US-China Workshop on Ground Improvement in Florida in 2009, and some of the soil improvement technologies were presented at this workshop. Since the workshop in 2009, these technologies have been advanced and new technologies have emerged.

To benefit the soil improvement community in the U.S., the ASCE G-I Soil Improvement Committee led by Dr. Kord Wissmann (past chair) and Prof. Jie Han (current chair) submitted a proposal in October 2017 to the G-I board to organize a scan tour followed by a workshop in Summer 2018. The main purpose of the tour and workshop was to gather first-hand knowledge and then disseminate the findings to the community about the latest ground improvement technologies utilized in China. This proposed scan tour was approved by ASCE G-I in April 2018 with travel funding support.

The scope of the scan tour was to identify and document new and implementable soil improvement technologies successfully used in China, with the goal of implementing the technologies into the current U.S. GeoTechTools selection system. The scan tour was organized from May 23 to 26, 2018 and the second China-US workshop on Ground Improvement technologies was held on May 27, 2018, which was in conjunction with the major international conference – GeoShanghai International Conference.

1.2. Scan Tour Team

The scan tour team consisted of 12 ground improvement experts from universities (Profs. Jie Han, Jie Huang, Prabir K. Kolay, Cheng Lin, Leon van Paassen), consulting firms (Drs. Jose Clemente, James Collin, Guoming Lin, and Antonio Marinucci), and contractors (Mr. Rob Jameson, Dr. Lisheng Shao, Dr. David Yang) in the US and Canada. This tour was led by Prof. Jie Han and Dr. Jose Clemente. Figure 1.1 shows the team members and two students at the Xiaoxing project site in Zhejiang Province.

Fig. 1.1. Team members at the Xiaoxing project site (from left to right: Leon van Paassen, Jie Han, Xiaoming Lou (project chief engineer), Guoming Lin, Cheng Lin, Prabir K. Kolay, Lisheng Shao, James Collin, Jie Huang, Antonio Marinucci, Jose Clemente, David Yang, Liya Wang (Ph.D. student from China), Rob Jameson, and Panpan Shen (formerly Ph.D. student from China)

1.3 Scan Tour Route and Visited Technologies

The scan tour started on May 23, 2018 and ended on May 26, 2018. Figure 1.2 shows the scan tour route from Shanghai, Shaoxing, Hangzhou, Taizhou, Hangzhou, Fuyang, Deqing to Shanghai. Table 1.1 lists the dates, locations, and technologies visited on this tour.

Table 1.1 Dates, Locations, and Technologies Visited

Date	Location	Technologies
5/23/2018	Shanghai	Diaphragm wall
5/24/2018	Shaoxing, Zhejiang Province	Dynamic compaction with vacuum dewatering
	Hangzhou, Zhejiang Province	Ground anchors by jet grouting
5/25/2018	Taizhou, Zhejiang Province	Vacuum preloading and electro-osmosis dewatering/consolidation
5/26/2018	Fuyang, Zhejiang Province	Diaphragm wall
	Deqing, Zhejiang Province	Deep mixing, surface soft soil stabilization, and bamboo-shaped piles

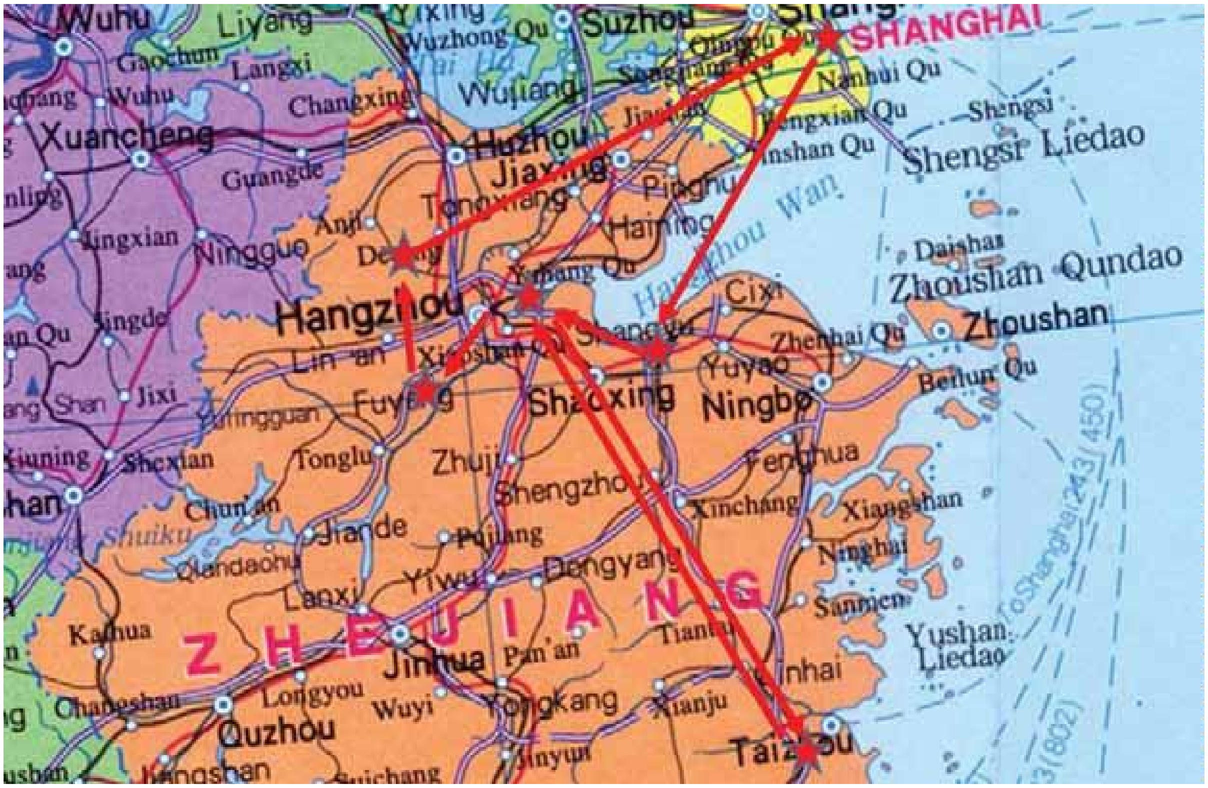


Fig. 1.2. Scan Tour Route

1.4 Report Organization

The scan tour team visited six project sites in Shanghai and Zhejiang Province, China, where eight ground improvement technologies were adopted. Chinese researchers and/or engineers presented other ground improvement technologies at the 2nd China-US Workshop on Ground Improvement Technologies. This report documents these ground improvement technologies, examines these technologies versus those used in the US, and makes recommendations for adopting some of the technologies or techniques. In the appendix of this report, the proceedings of the 2nd China-US Workshop on Ground Improvement Technologies are included.

2. DIAPHRAGM WALLS

2.1 Introduction

Diaphragm wall methods are employed extensively in the Shanghai region for the support of deep excavations for both commercial (buildings) and public works (infrastructure and utilities). In general, the construction methods and equipment employed are consistent with U.S. experience and practices.

The typical sequence of diaphragm wall construction is summarized in the following steps:

- Soil is excavated in vertical panels with dimensions ranging from 600 mm to 1.5 m (2.5 to 5 ft) in width and up to 3.0 to 4.6 m (10 to 15 ft) in length, to the required depth.
- The panels are maintained open by using a drilling support fluid (mineral-based slurry (bentonite) is common) throughout the excavation process for panel stability and integrity.
- Excavation of a panel is performed using either a crane-suspended clamshell grab or hydromill.
- At the completion of the excavation, the slurry is cleaned and/or exchanged prior to the placement of the steel reinforcing cage.
- Each panel is filled with tremie placed concrete.
- Continuous walls are constructed by sequenced operations:
    - Primary panels are excavated and concreted.
    - After the concrete within the primary panels has set (not achieved full strength), secondary panels are excavated and concreted end-to-end and overlapped with primary panels, thereby forming a continuous structural wall.

2.2 Project Sites

Two project sites were visited: (1) Suzhou River Deep Drainage and Storage Facility, Shanghai: Yunling West Shaft, and (2) Support of Excavation Walls for Metro Station, Fuyang. However, only the Shanghai project will be described, as many of the details (e.g., equipment, tooling, drilling fluids, etc.) at the Fuyang project were similar to those for the Shanghai project. Other diaphragm wall operations were observed on numerous other sites while travelling within the region. The Yunling Shaft project comprises a very deep excavation in relatively soft alluvial soils, with corresponding depth of diaphragm wall required for support of excavation and to maintain invert stability. Both the excavation and diaphragm wall depth lie at the limits of North American experience in similar ground.

2.3 Suzhou River Deep Drainage and Storage Facility, Shanghai: Yunling West Shaft

The current drainage systems of Shanghai have insufficient capacity during intense rainfall events and rely on overflow flood discharge into the Suzhou River. The Deep Drainage Project was planned as a mitigation measure to discharge rainwater for a 5-year rainfall event for 1 hour with no water accumulation or a 100-year rainfall event for 1 hour with less than 150 mm water accumulation. Figure 2.1 shows the layout of the deep drainage tunnels including the project site the team visited, relative to the Suzhou River and the Huangpu River. Figure 2.2(a) shows the test section with the first complex facility connected to the second complex facility (i.e., the project site) by a 1.7 km (1.1 mi) long tunnel. The rainfall collection-drainage system shown in Figure 2.2(b) consists of a series of deep circular shafts approximately 60 to 70 m (195 to 230 ft) in depth, which will be connected by approximately 15.3 km (9.5 mi) of deep tunnels or pipelines with diameters ranging from 8 to 10 m (26 to 33 ft) and at depths of 40 to 60 m (130 to 195 ft) along the Suzhou River.

The scan tour visited the Yunling West Shaft site to observe the diaphragm wall construction of one of the deep shafts and the ancillary complex. This site is located on the north bank of the Suzhou River, just west of the Shanghai Middle Ring Road (inner traffic loop). At the time of the scan tour, a pilot section consisting of a tunnel section crossing below the river and approximately 1.67 km (1.0 mi) in length connecting two deep shafts was under construction.

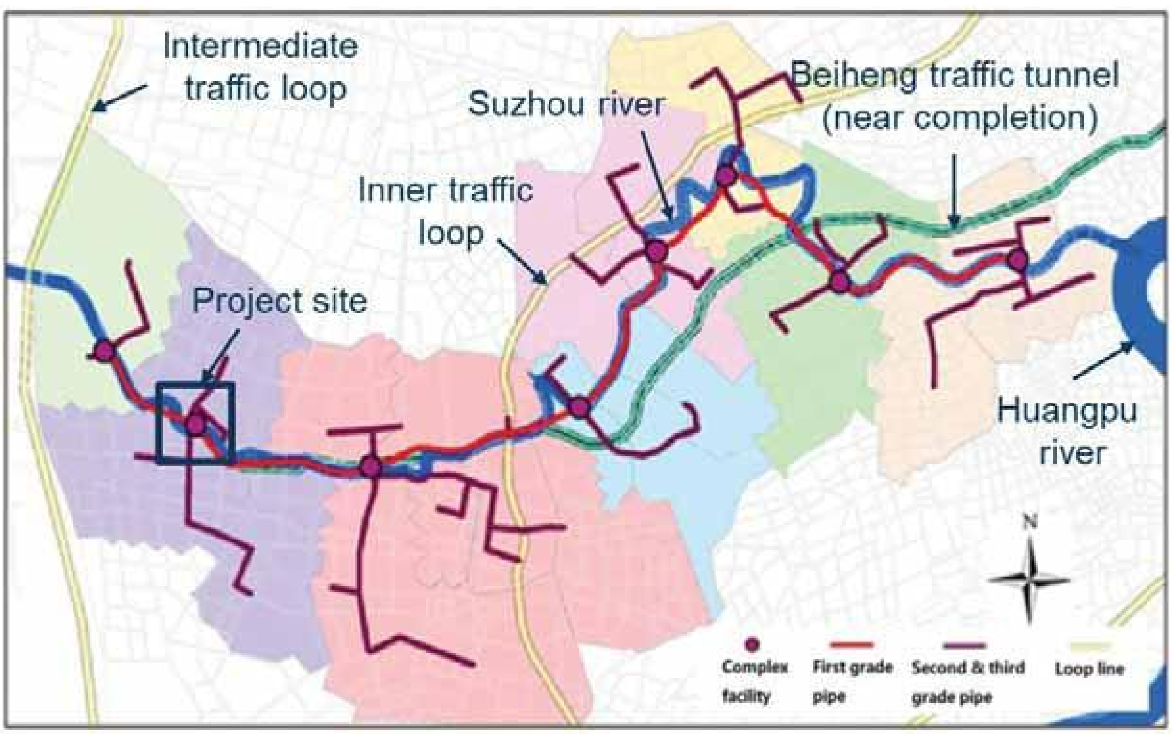
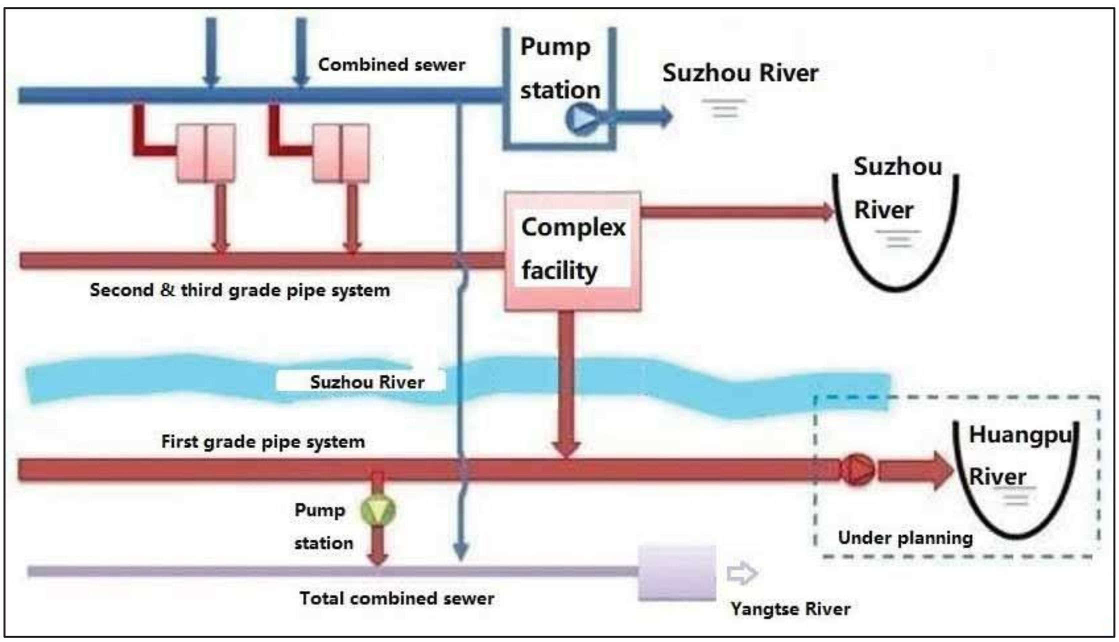


Fig. 2.1. Plan view of project alignment (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

(a) Test section



(b) System components

Fig. 2.2. Schematic view of the rainfall collection-drainage system (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

2.3.1 Project Scope

The site excavation is developed in four segments. The geometries of the various wall segments are summarized in the following table and on Figures 2.3 and 2.4.

Table 2.1 Diaphragm Wall Geometry (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

Segment	Description	No. of Panels	Dimensions (in plan)	Wall Depth	Wall Thickness	Depth of Excavation
---	Test Panels	3	---	150 m (492 ft)	1.5 m (59 in)	---
1	Circular Shaft	46	34 m (112 ft) in diameter	105 m (345 ft)	1.5 m (59 in)	59.6 m (196 ft)
2	Storage Chamber	35	37 by 57 m (121 by 187 ft)	105 / 80 m (345 / 262 ft)	1.2 m (47 in)	33.8 m (111 ft)
3	Connection Chamber	25	12 by 14 m (39 by 46 ft)	80 m (262 ft)	1.2 m (47 in)	33.3 m (109 ft)
4	Perimeter Wall	33	40 by 61 m (131 by 200 ft)	105 m (345 ft)	1.0 m (39 in)	16.7 (55 ft)

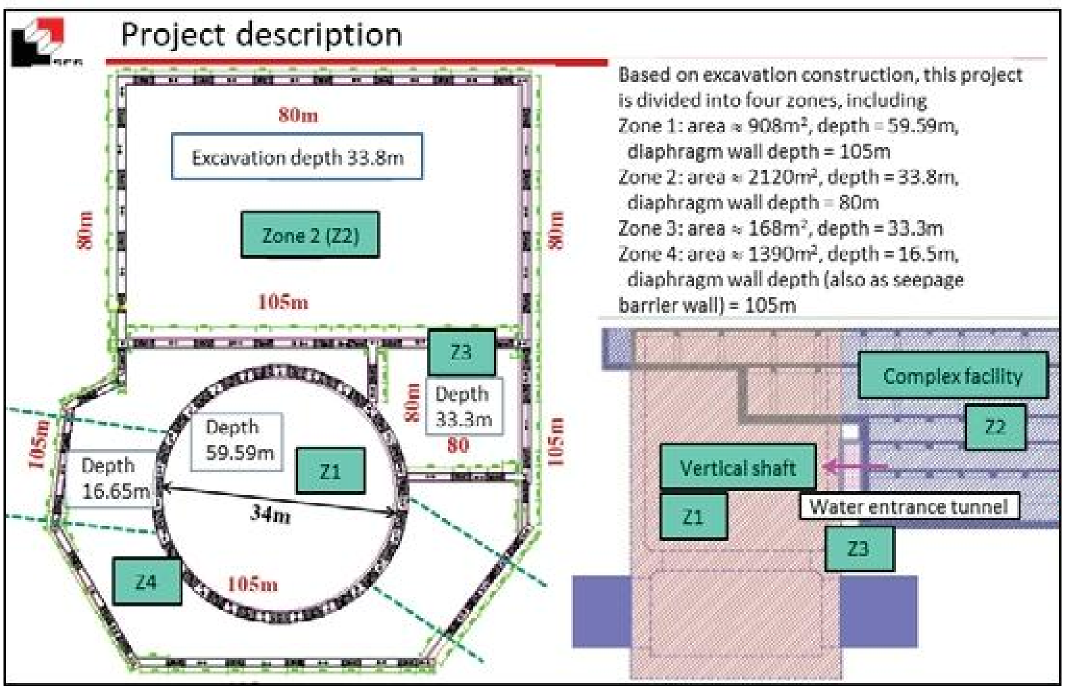
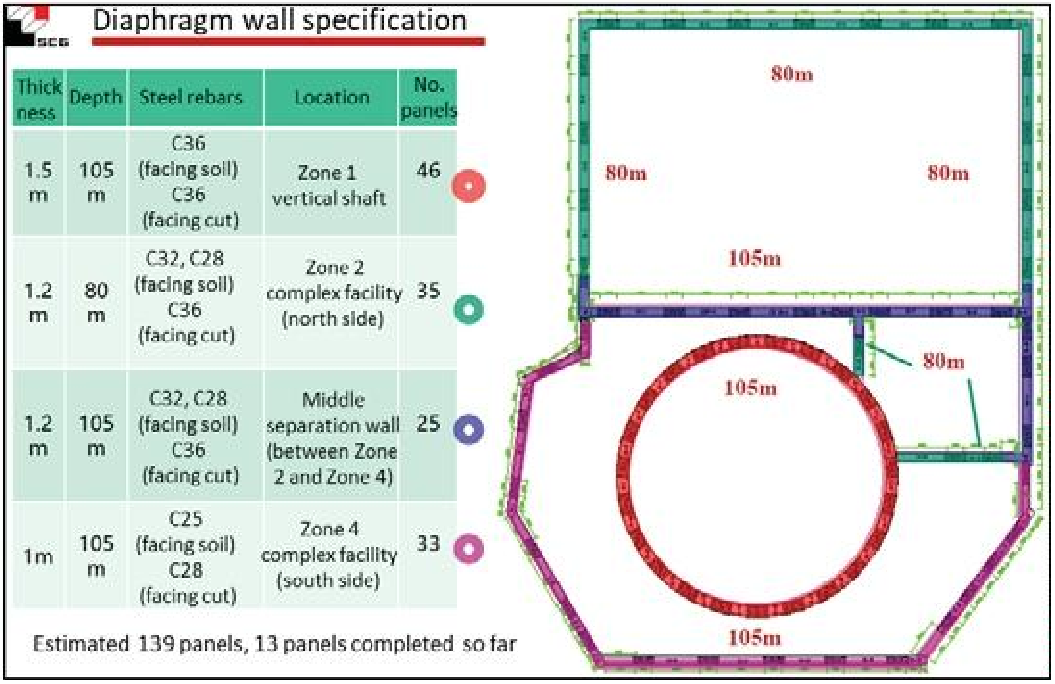


Fig. 2.3. Plan view and section of the four work segments (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)


Diaphragm wall specification

Thickness	Depth	Steel rebars	Location	No. panels
1.5 m	105 m	C36 (facing soil) C36 (facing cut)	Zone 1 vertical shaft	46
1.2 m	80 m	C32, C28 (facing soil) C36 (facing cut)	Zone 2 complex facility (north side)	35
1.2 m	105 m	C32, C28 (facing soil) C36 (facing cut)	Middle separation wall (between Zone 2 and Zone 4)	25
1m	105 m	C25 (facing soil) C28 (facing cut)	Zone 4 complex facility (south side)	33

Fig. 2.4. Plan view and dimensioning of the four work segments (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

2.3.2 Objectives

The concrete diaphragm walls are being constructed to provide support of excavation (SOE) and groundwater control for the construction of the deep shafts for access to the tunnel and pipelines, to the rectangular storage chamber, and for the connection between these structures. The concrete diaphragm walls will provide temporary SOE and will be incorporated into the final work as permanent structural elements. Structural facing will be added onto the exposed face of the diaphragm walls after the completion of the excavation. For the circular deep shaft, the compression ring configuration provides the necessary lateral earth support for stability and deformation. For the structures, temporary concrete walers and bracing will be employed for lateral support during excavation, with floor slabs providing the permanent lateral restraint.

2.3.3 Site Conditions

The site (Figure 2.5) is located adjacent to the north flood wall of the Suzhou River, approximately 1 km (0.6 mi) west of Shanghai Middle Ring Road. The site complex extends approximately 200 m (655 ft) east to west along the river and extends approximately 100 m (330 ft) north from the flood wall. This area incorporates the shaft and pump station construction area, project offices, slurry plant, rebar cage fabrication facilities and ancillary construction support zones. The area is within urban Shanghai; however, there are only a few nearby structures. An existing rainwater pump station lies to the east of the site, with all other notable structures located more than 100 m (330 ft) from the shaft complex.

Fig. 2.5. Aerial view of the project site (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

Soil Type

Soils within the depth of investigation (165 m or 540 ft) are Quaternary, Late Pleistocene and Holocene sediments, which consist mainly of clays, silty soils, and sands. The soils have relatively uniform layers of fine grained soils, interlayered with sand and/or gravel (aquifers). Based on the age of deposition, geological formation, and physical and mechanical properties, the ground can be divided into 12 major soil layers (Figure 2.6). The cutoff wall depths for different areas within the project site extend through artesian aquifers at or closely to underlying subgrade to penetrate into units of fine-grained soil.

2.3.4 Equipment

The equipment used to excavate the deep diaphragm walls consists of a Bauer BC40 Hydromill, mounted on a Bauer MC128 crane (Figure 2.7) for excavation of the slurry walls that extend to a depth of approximately 105 m (345 ft). The equipment was procured and set-up to excavate panels for depths up to 150 m (492 ft). Two other diaphragm wall machines were used to excavate the shallower wall panels, which extended to a depth of approximately 80 m (262 ft) and consisted of a Bauer BC40 hydromill on a Bauer MC96 base and a Jintai SG60A hydromill (Figure 2.8). The equipment used on this project site represents the global state of practice for deep diaphragm wall construction and is consistent with equipment employed in North America for similar scopes of work.

Various support equipment was used to move materials, tooling, and equipment around the project site. Two large support cranes with capacities of 400 and 500 tonne (440 and 550 ton) were employed primarily for handling the steel reinforcing cages.

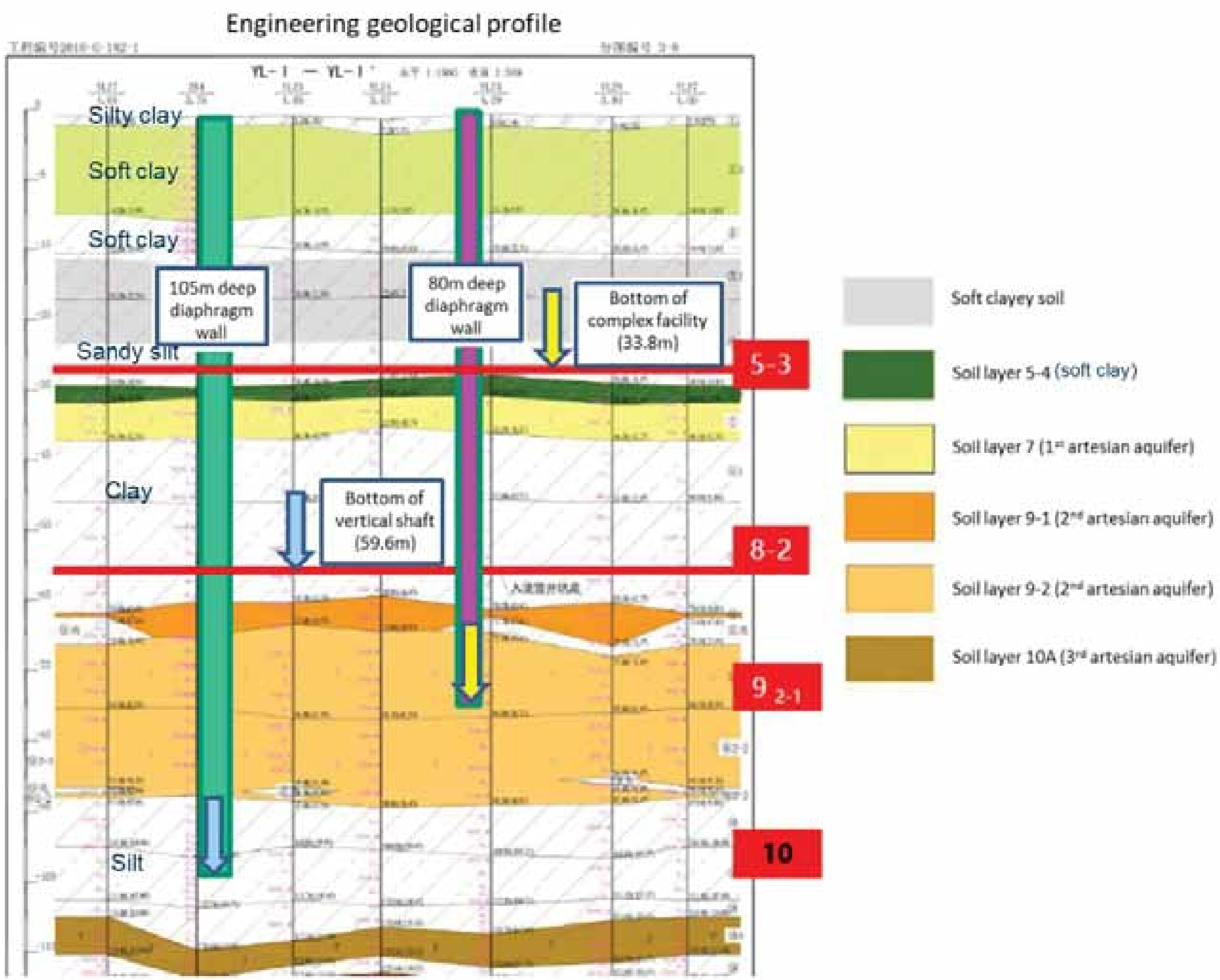


Fig. 2.6. Subsurface profile at the project site (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

Fig. 2.7. Bauer BC40 hydromill

Fig. 2.8. Bauer BC40 hydromills & Jintai SG60A hydraulic clamshell

Fig. 2.9. Support cranes and hydromills

The slurry plant is a custom fabricated facility, comprising batching, holding and settlement tanks constructed using cast-in-place concrete, which is covered by a temporary roof (Figure 2.10). Desanding and desilting units are configured on the south edge of the slurry plant for separation of solids (Figure 2.11). Spoils are loaded out using an excavator for off-haul and disposal. Electric powered pumps are employed to circulate the slurry within the system. There was a separate structure for quality assurance for the various activities performed on site (Figure 2.12).

Fig. 2.10. Hydration and settling tanks

Fig. 2.11. Desanding and desilting units

Fig. 2.12. Quality assurance / quality control performed on the bentonite slurry

Miscellaneous tooling, end stops, fabrication beds, cleaning mechanisms, and tremie system are illustrated in Figures 2.13 through 2.18. Cut sheets for the various equipment are commonly available from the respective manufacturers.

Fig. 2.13. Tremie pipes

Fig. 2.14. Concrete placement operation

Fig. 2.15. Welding of reinforcement cage

Fig. 2.16. Completed reinforcement cage

Fig. 2.17. Specially-designed back scratcher

Fig. 2.18. Custom-designed end stops

2.3.5 Design

The central component of the construction operation is the deep access shaft that has an internal diameter of approximately 34 m (112 ft) and an excavation depth to approximately 60 m (196 ft). The shaft was designed as a compression ring comprising 46 individual diaphragm wall panels to create the circular structural element. Each panel has a thickness of 1.5 m (59 in), an overall depth of 105 m (345 ft), and a toe embedment of approximately 45 m (148 ft). Steel reinforcing cages are installed in each panel prior to concrete placement. To facilitate groundwater control and uplift resistance, the toe of the wall extends through the thick aquifer directly below the shaft and penetrates the underlying deep clay unit.

A secondary perimeter wall will be constructed around the shaft on the west, south and partially on the east sides, with each of the panels extending to a depth of 105 m (345 ft). This wall mainly provides additional groundwater control, and the depth of excavation between the deep shaft and the secondary wall will be only approximately 16.7 m (55 ft). Due to the relatively shallow excavation of the secondary wall, the width of each panel will be only 1.0 m (39 in).

Along the north and northeast walls of the secondary perimeter wall, the width of the panels comprising this wall will be 1.2 m (47 in). These diaphragm wall panels provide the dual function of serving as a secondary perimeter around the shaft and of forming permanent walls for the excavations for the deep storage chamber and connection chamber, which extend over 33 m (108 ft) deep. The remaining walls of these two structures are constructed with panels with a width of 1.2 m (47 in) that extend to a depth of 80 m (262 ft). The toe embedment for these two excavation zones exceeds 46 m (151 ft).

Although the deep shaft is constructed as a circular compression ring, the remaining deep excavations are rectangular or non-uniform in shape and will be supported using cast-in-place concrete bracing during excavation. The excavation sequence is constrained to complete the deep circular shaft and then the rectangular north storage chamber. Once these two facilities are excavated and completed with the internal cast-in-place concrete liners (thickness of 420 mm or 16.5 in), the ancillary excavations of approximately 33.3 m (109 ft) in depth for the tie-in between the two facilities and of approximately 16.7 m (55 ft) in depth around the shaft perimeter will be completed.

The diaphragm wall cages included tubes for non-destructive testing and pre-installed tubes at the ends of each panel to allow for introduction of ground freezing systems, if required to assist in the sealing of the joints against water inflow.

2.3.6 Installation

The diaphragm wall was constructed in sequential primary and secondary panels. Surface guide walls were constructed to maintain alignment of all the panel and wall configurations. The requirement for panel verticality was 1/1000 for each of the four walls. The site visit review focused on the deep shaft, which used 1.5 m (59 in) wide by 2.8 m (9.2 ft) long panels. The overlap between the primary and secondary panels was approximately 300 mm (12 in). Surface block-outs (guides), extending to a depth of approximately 5 m (16.4 ft), were installed at the ends of each primary panel to allow initial positioning and alignment of the hydromill for secondary panel cutting. The joints between panels were constructed by the hydromill as it milled or ground through the concrete of the primary panels at each end of the secondary panel. The minimum compressive strength of the concrete was specified as 40 MPa (5,800 psi) and had to provide a seepage pressure resistance of 1.2 MPa (175 psi). Concrete placement was performed using the tremie method, as it was placed into and had to displace the bentonite slurry.

2.3.7 Test Program

A pre-production testing program was performed between December 2017 and January 2018 to verify the construction program could satisfy the project specifications and performance criteria: attain the required depths and tolerances for panel excavation, placement of the steel reinforcement cage, and successfully place the concrete for the panels using tremie methods. Verticality surveys were performed using a Koden system at depth intervals of approximately 30 m (100 ft) throughout the excavation.

For the test program, the panel depth was 150 m (492 ft), which was 45 m (148 ft) deeper than required for the production phase. The test panels were reinforced with 145 m (476 ft) long steel reinforcement cages, which were hoisted and spliced in four sections. For the test panel, it took approximately 8 to 10 hours to install the reinforcement cage. A summary of key information obtained during the test program is provided in the table below.

Table 2.2 Summary of Key Construction Information (source: Shanghai Foundation Engineering Group CP., LTD., the Third Engineering Company)

Panel No.	Start Date	Installation Time (hours)	Measured Verticality	Overbreak
ZQ2	30 Dec 2017	120	1/3750	114%
ZQ3	06 Jan 2018	76	1/1600	106%
ZQ2-3	12 Jan 2018	297	1/1000	109%

Production Phase

The scan tour team visited the site on 23 May 2018. At that time, the diaphragm wall construction was ongoing and no excavation had commenced. The MC128/BC40 hydromill system was not operating; however, ancillary equipment was working on the installation of perimeter diaphragm walls. Observations made regarding the construction being performed include:

- Rebar cages are constructed on-site in segments up to 30 m (100 ft) in length. The cage sections are hoisted to a vertical position using two cranes and are then spliced over the open panel that is filled with bentonite slurry.
- Concrete is placed through tremie pipes that have an internal diameter of 255 mm (10 in). However, details of the concrete mix design were not available. The tremie is supported and agitated using a tripod hoisting rig.
- After the concrete has been placed and hardened, NDT testing using the crosshole sonic logging (CSL) method is performed on the concrete to evaluate the integrity of the placed concrete.
- The rebar cages include steel pipes that can act as freeze conduits, if required, for joint sealing. Our onsite guides also described consideration of grouting at the exterior of joints for supplemental sealing purposes.

2.3.8 Research Work and Key Findings

The Yunling West Shaft consists of a diaphragm wall compression ring with a thickness of 1.5 m (59 in) and a wall depth of 105 m (345 ft) with a planned excavation to a depth of 59.6 m (196 ft). This project reflects a global state-of-practice with respect to depth of wall construction and excavation in the relatively weak alluvial soils present in Shanghai. The diaphragm wall construction operations reflect the international standard of practice for similar works. In addition, the construction equipment, work program, and quality control (QC) approach used at this site were consistent with expectations for this scope of work if performed in North America or similar markets.

The key observations made for this project and deference to local practice include:

1. The extensive use of concrete as a relatively low-cost material for (a) the proposed internal bracing systems for the support of excavation (as compared to using steel) and (b) the custom-fabricated slurry plant (as compared to using to tank farms).
2. The construction program involved a 3-level contingency program for joint sealing
   a. Milling a 300 mm (12 in) overlap into each primary panel using the hydromill.
   b. Pre-installed steel pipes for a post-construction freezing system at the panel ends.
   c. Option for exterior grouting patterns at the panel joints.

2.3.9 Lessons Learned and Recommendations

Follow up on the actual performance of the diaphragm wall system during excavation would be very informative. The 3-levels of joint sealing precautions appeared conservative; however, review of the actual performance and joint quality will assist in the evaluation and relevance to future construction works. This project can be used as a successful case study for similar future projects.

3. DYNAMIC COMPACTION WITH VACUUM DEWATERING

3.1 Introduction

Dynamic compaction is a common ground improvement technology, which is used to densify weak soil to increase soil modulus and strength, and to reduce liquefaction potential. It is most suitable for partially saturated, non-plastic or low plasticity soil (e.g., plasticity index < 8) where the groundwater table is sufficiently deep. However, this method may also be effective for low permeability silt and silty clay, provided a proper drainage and/or dewatering system is installed.

The project site that the scan tour team visited consisted of soft dredged silt and silty clay and had the groundwater table at the ground surface. Under this condition, dynamic compaction alone is not effective. To improve the effectiveness of dynamic compaction, vacuum dewatering was implemented by installing vacuum tubes to both shallow and great depths, thereby lowering the groundwater table and assisting with the dissipation of excess pore water. This section provides a brief overview of the combined vacuum dewatering and dynamic compaction technology and of the applications of this technology to two road projects with similar soil conditions. One project visited by the scan tour team was still under construction, while the construction of the other project not visited by the team was completed.

3.2 Description of the Technology

Dynamic compaction is performed by repeatedly dropping a tamper (weight 5 to 40 tons [4.5 to 36 U.S. ton]) from heights of 10 to 40 m (33 to 130 ft) onto the ground surface, with a maximum effective treatment depth of approximately 10 m (33 ft). The impulse force generated by the dropped mass improves the ground resulting in lower void ratios and higher density. Since the 1960s, dynamic compaction has been significantly advanced and widely used (Han 2015). This technique is most effective for sandy soil or low plasticity soil where the groundwater table is deeper than approximately 2 m (6.5 ft) from the ground surface. The effectiveness of dynamic compaction becomes questionable in low permeability silt and/or clay and a high groundwater table.

In such circumstances, dewatering and drainage measures are necessary to supplement dynamic compaction to dissipate the excess pore water. Vacuum dewatering is a process of drawing the water out of the ground through preinstalled vertical vacuum tubes and horizontal pipes by applying vacuum. This technology is especially useful when the ground is composed of saturated soft dredged silt and is inaccessible by construction equipment. Vacuum dewatering can lower the groundwater table and turn the saturated silty soil into a surface crust to support equipment or machinery needed to perform the dynamic compaction. Moreover, vacuum dewatering acts as an efficient drainage system to dissipate excess pore water generated during dynamic compaction.

The advantages of combined dynamic compaction and vacuum dewatering:

(i) Quick process,

(ii) No fill or temporary matting (i.e., no preload or surcharge fill),

(iii) Cost effectiveness for massive treatment, and

(iv) Straightforward and relatively simple installation and construction equipment.

3.3 Project Sites and Subsurface Conditions

The project site is close to the city of Shaoxing, Zhejiang Province, which is approximately 180 km (112 mi) south of Shanghai, as shown in Fig. 3.1. The project is under construction and is a part of a large development called the Hangzhou Bay Industrial Park. The objective of the project is to improve the soil condition for construction of a 1 km (0.6 mi) long municipal road. The total treatment area is approximately 28,000 m^2 (6.9 acre).

Fig. 3.1. Location of project site (the map showing the route the team took to the site)

According to the contractor, the Shanghai GeoHarbour Co., the subsurface consists of a layer of recently dredged hydraulic fill (mainly silt and silty sand) with a thickness of 1.5 to 2.0 m (5 to 6.5 ft) that was deposited atop a thick silt layer with a thickness of 17 to 20 m (55 to 66 ft). The silt layer is underlain by soft silty clay. The purpose of adding a layer of hydraulic fill is to develop a working platform so that mining and hauling of gravel can be avoided. Discussion about how to form a working platform using the hydraulic fill will be discussed below.

3.4 Construction Process

The goal of the ground improvement is to improve the soil to achieve a minimum allowable bearing capacity of 120 kPa (2,500 psf), and a resilient modulus no less than 25 MPa (3,625 psi). The depth of improvement was between 6 and 8 m (20 to 26 ft) (i.e., within the silt layer). The construction process consists of disturbing the hydraulic fill, installing the vacuum tubes, and performing the vacuum dewatering along with dynamic construction as described below:

(1) A ditch around the treatment area is constructed to allow water egress from the hydraulic fill. An excavator is used to disturb and liquefy the hydraulic fill, which helps to accelerate the drainage, while densifying the fill.

Fig. 3.2. Disturbance of hydraulic fill to a denser state
(source: Shanghai GeoHarbour Co.)

(2) The vacuum dewatering system includes vertical vacuum tubes and horizontal pipes, which are installed manually in a pattern as shown in Figs. 3.3 and 3.4. The vertical vacuum tubes are installed to two different depths. In Fig. 3.3, the gray and black dots denote tubes installed to a depth of 3 m (9.8 ft) and 6 m (19.7 ft), respectively. This stage of construction helps lower the groundwater table and consolidate the surface soil to form a working platform. The short and long vacuum tubes will remain in place for the subsequent dynamic compaction.

(3) After the ground surface gains adequate strength to support the needed equipment, dynamic compaction is carried out in three passes, as shown in Figs. 3.5 and 3.6.

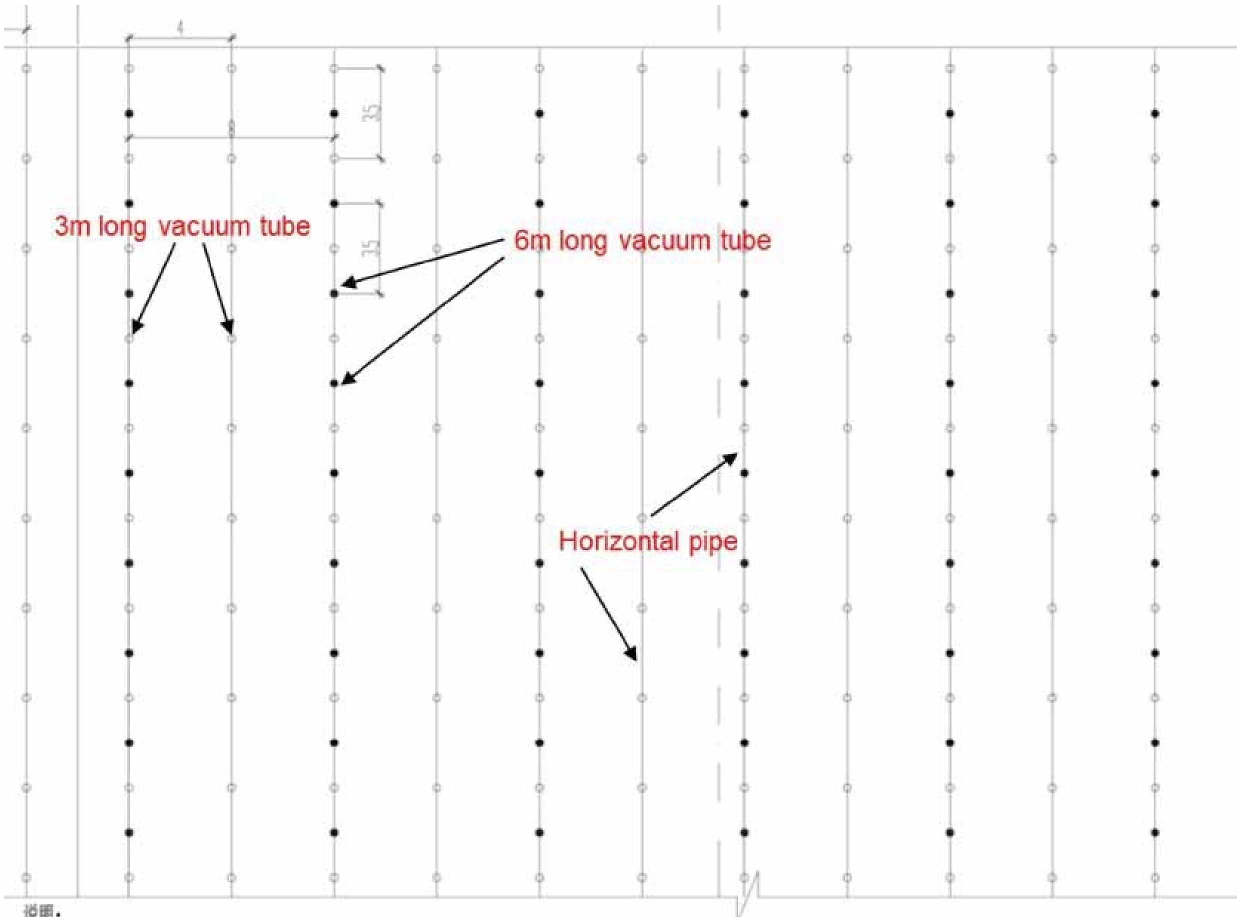


Fig. 3.3. Pattern of installation of vacuum tubes (source: Shanghai GeoHarbour Co.)

(a)

(b)

(c)

Fig. 3.4. Photographs of the vacuum dewatering system: (a) installation of vacuum tubes, (b) completed installation, and (c) water drained to ditch (source: Shanghai GeoHarbour Co.)

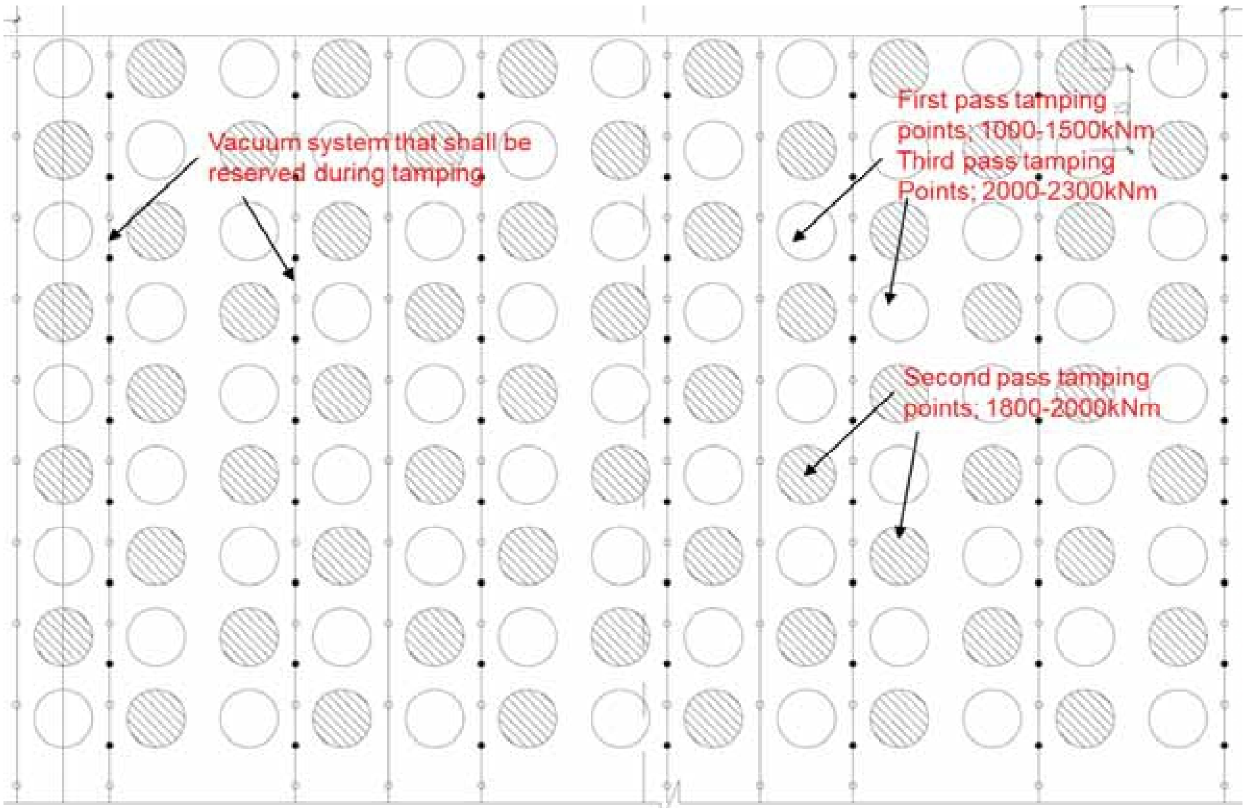


Fig. 3.5. Design of dynamic compaction (source: Shanghai GeoHarbour Co.)

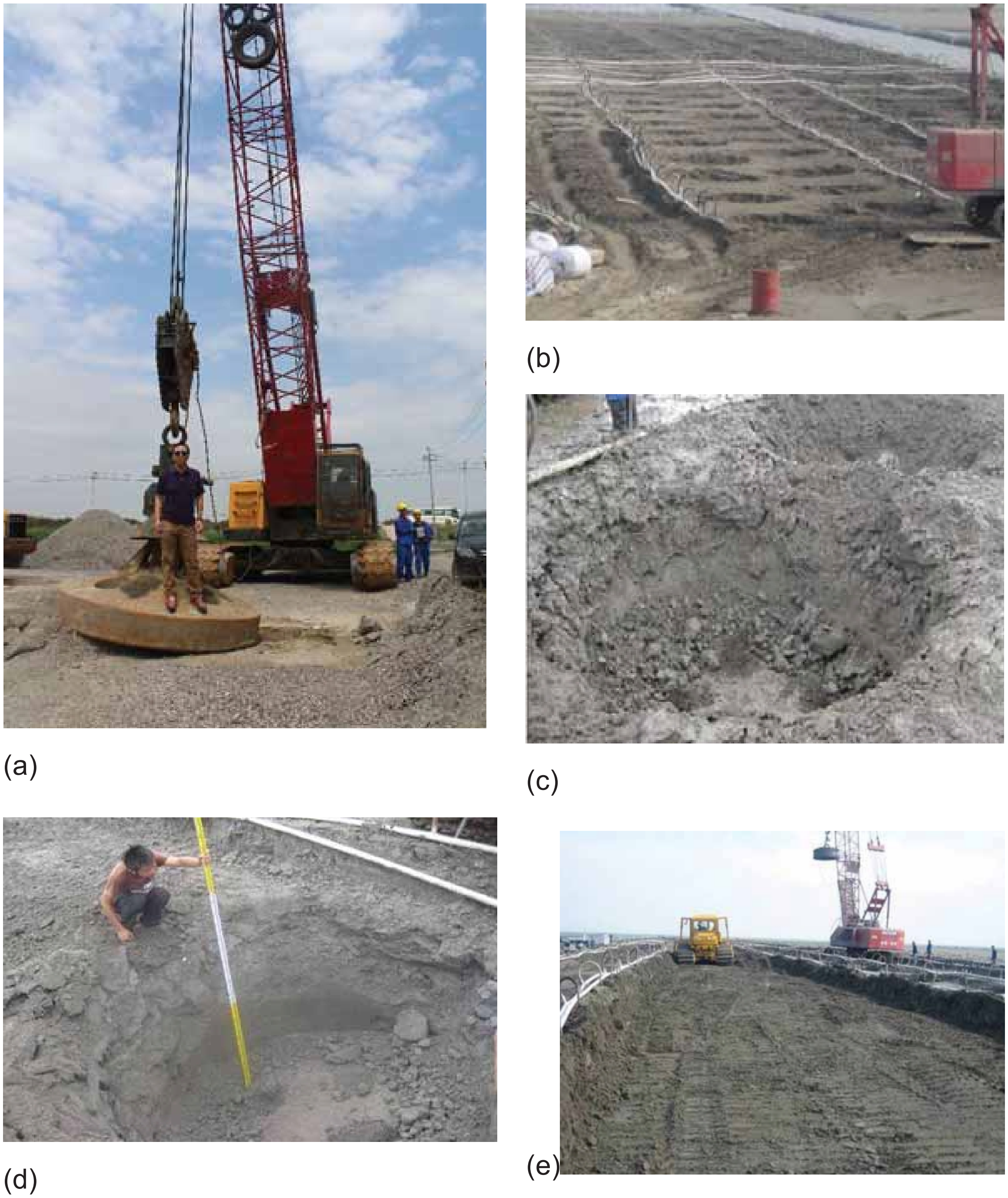


Fig. 3.6. Photographs of the dynamic compaction process: (a) equipment, (b) after dynamic compaction, (c) a crater after 1st pass of tamping, depth of 1.5 to 2.0 m (5 to 6.6 ft), (d) a crater after 2nd pass of tamping, crater depth 1.2 to 1.5 m (4 to 5 ft) (source: Shanghai GeoHarbour Co.), and (e) leveling ground after dynamic compaction (large settlement after compaction)

3.5 Monitoring during and after Construction

To ensure the quality of the improvement, multiple parameters were monitored before and after dynamic compaction, including water content, pore water pressure, ground settlement, CPT tip resistance, and bearing pressure. Tables 3.1 and 3.2, and Figs. 3.7, 3.8, and 3.9 show the test results from one previous project.

Figure 3.7 shows the pore water pressures at different stages of dynamic compaction. It can be seen that the excess pore water pressure quickly dissipated to zero with the aid of vacuum dewatering within 2 to 5 days after the completion of the dynamic compaction. The drastic decrease in the water content from dynamic compaction is highlighted in Table 3.1, where the average decrease was approximately 30% in the upper 2.0 m (6.6 ft). As summarized in Table 3.2, dynamic compaction resulted in a total settlement of approximately 72.6 cm (28.6 in). The CPT tip resistance profiles before and after dynamic compaction are shown in Fig. 3.8. Improvement of the soil was considerable down to a depth of 10 m (33 ft); however, the degree of improvement decreased considerably with depth. The plate loading test results after dynamic compaction are presented in Fig. 3.9 and the allowable bearing capacity was determined to be 140 kPa (2,925 psf), which exceeded the minimum required capacity of 120 kPa (2,500 psf).

Overall, the site conditions were remarkably improved and the combined vacuum dewatering and dynamic compaction technology was effective in treating the soil at the project sites.

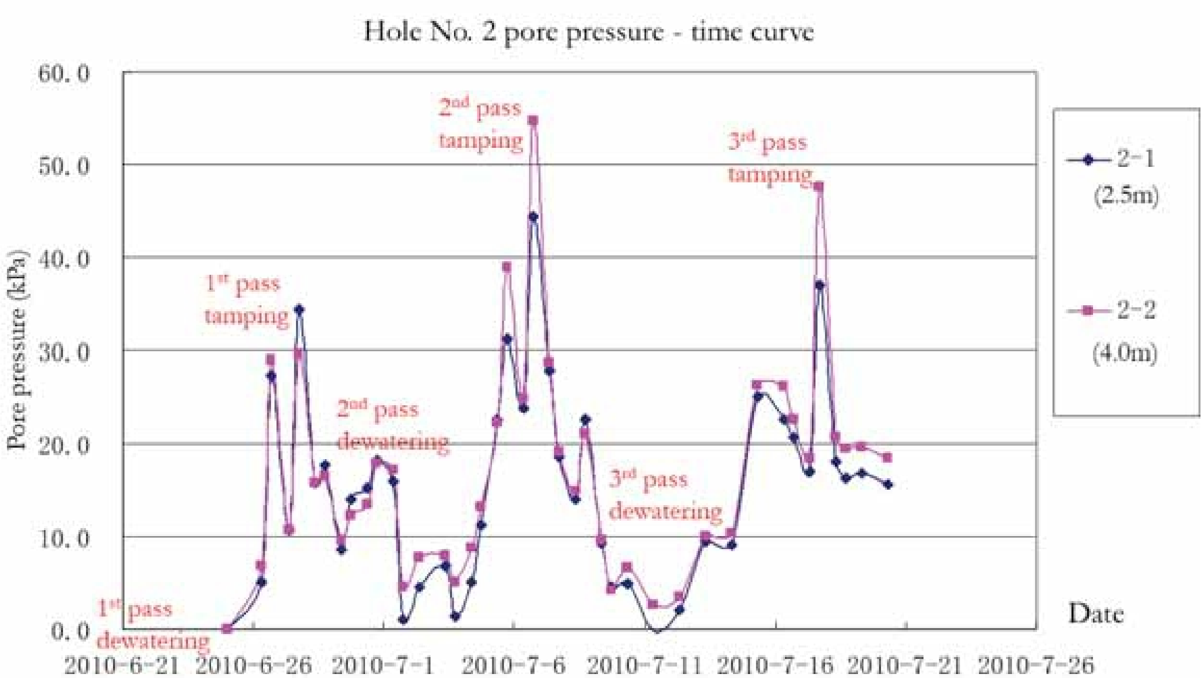


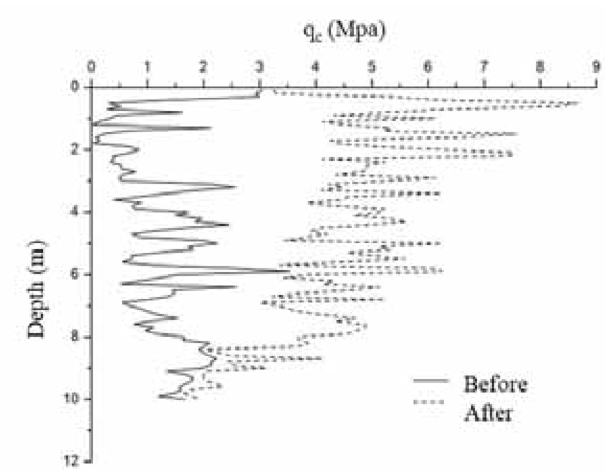
Fig. 3.7. Variation of pore water pressure during dynamic compaction in Hole 2 (source: Shanghai GeoHarbour Co.)

Table 3.1 Variation of water content before and after dynamic compaction (source: Shanghai GeoHarbour Co.)

Sample ID	**Sampling depth (m)**	**Water content pre-treatment**	**Water content post treatment**
1	1	39.7%	24.7%
2	1	37.7%	24.6%
3	2	35.2%	28.6%
4	2	35.4%	26.2%

Table 3.2 Settlement of ground during dynamic compaction (source: Shanghai GeoHarbour Co.)

Process	**1st pass tamping**	**2nd pass tamping**	**3rd pass tamping**	**Ironing**
Settlement (cm)	23.4	31.3	7.1	10.8
Total settlement (cm)	72.6			



Depth	Average qc (MPa)		Improvement rate
0~6m	Before	0.96	448%
	After	5.26	
6~8m	Before	1.89	119%
	After	4.33	
8~10m	Before	1.76	49%
	After	2.63	

Fig. 3.8. Changes in CPT tip resistance before and after dynamic compaction (source: Shanghai GeoHarbour Co.)

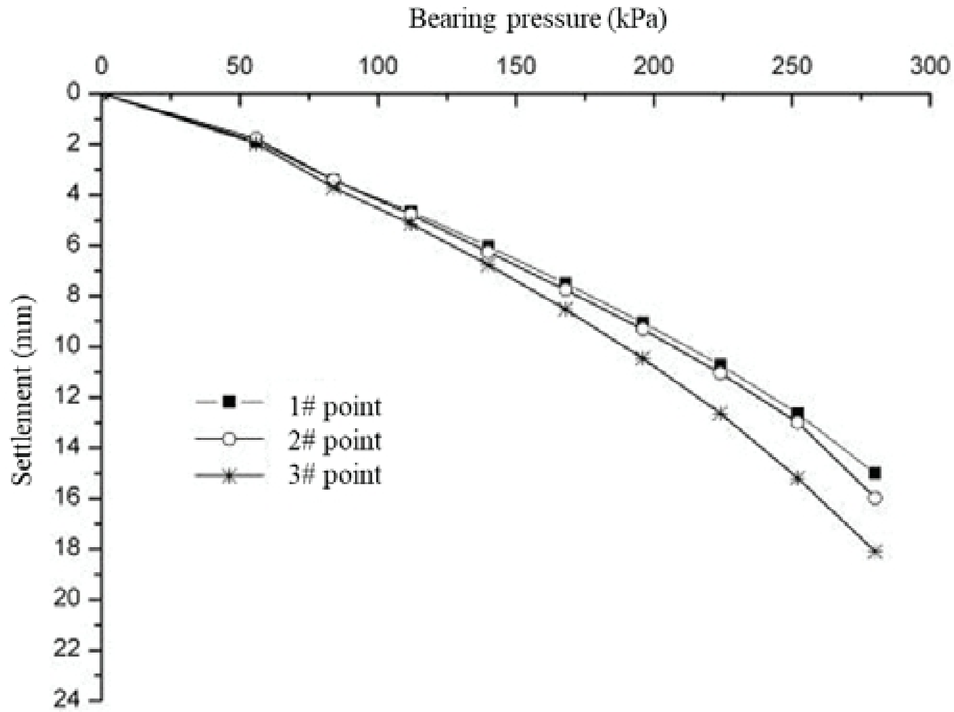


Fig. 3.9. Plate loading tests after dynamic compaction
(source: Shanghai GeoHarbour Co.)

3.5 Research Work and Key Findings

It is reported that the combined use of vacuum dewatering and dynamic compaction has been applied to even more challenging sites (e.g., very soft clays) (Liang et al. 2015) than the project site that the scan tour team visited. When it comes to treating soft clays, this technique is usually referred to as the high vacuum densification method (HVDM). The operational process follows repeated cycles of alternated vacuum dewatering and dynamic compaction, aided by the on-site monitoring. In comparison with conventional vacuum consolidation or dynamic compaction, HVDM is a fast ground improvement technology utilizing combination of active drainage, consolidation, and densification principles. It is promising for improving a massive site in a short time. The relevant research work (Liang et al. 2015) demonstrated that HVDM is effective in clays with permeability as low as 10^{-7} cm/s and vacuum dewatering is able to reduce the degree of saturation from 100% to approximately 75 to 85%. Both field tests and numerical simulation have been done to confirm the effectiveness of HVDM in treating soft clays (Liang et al. 2015).

3.6 Lessons Learned and Recommendations

The combined vacuum dewatering and dynamic compaction technology is considered highly effective and efficient for improvement of large scale sites, such as land reclamation, economic zone development along coast cities, highways, and port construction. The combined process overcomes the drawbacks inherited from vacuum consolidation (e.g., slow consolidation) and dynamic compaction (e.g., not effective in soft clays or in high ground water conditions). Moreover, it can create a hard surface layer for the access by construction equipment, thus avoiding the use of sands or gravels. To ensure the successful applications of this technology, the on-site monitoring during construction becomes critically important because the feedback from the monitoring data would help improve the operational process in the subsequent cycles, such as adjusting temper weight, grid spacing, pass number, and drop height. Usually two cycles of vacuum dewatering and dynamic compaction are sufficient to achieve satisfactory improvement in silty soils. Furthermore, this technology generally treats the soil up to a depth of 10 m and is not suitable for organic materials that typically have profound creep behavior.

4. DETACHABLE ANCHORS WITH JET GROUTING

4.1 Introduction

Ground anchors have been widely used in projects for excavation support, slope stabilization, and building foundation tie downs. In general, the anchor bond strength ranges from 0.2 to 3.1 MPa (30 to 450 psi) for rock anchors bonded in shale to granite, and 0.03 to 0.38 MPa (4 to 55 psi) for soil anchors in cohesive soils bonded in soft clays to very stiff sandy silts.

Jet grouting is a ground improvement technology that uses high pressure grout to jet and erode soils to form soilcrete (i.e., a mixture of the in-situ soil and the injected grout). The unconfined compressive strength of the soilcrete typically ranges from 0.3 to 3.0 MPa (45 to 435 psi). When combined with jet grouting, the anchors can achieve a high bond strength with the soilcrete, and the enlarged soilcrete/soil interface can accommodate low bond strength of a soil.

When used for excavation support, these anchors are usually installed at an inclined angle and extended outside the potential failure envelope. In some crowed cities, government regulations prohibit leaving steel reinforcement buried in the public property. The detachable anchors can be removed after the excavation is completed, conforming to the government regulations and saving construction cost.

The scan tour team visited an excavation project site in Hangzhou, Zhejiang Provence to learn how the detachable anchor application can be combined with jet grouting.

4.2 Description of the technology

4.2.1 Detachable Anchor

Fig. 4.1 shows that the detachable anchor includes an anchor base, anchor strands in sleeves, a specially made detachable anchor head, and an enlarged bonding zone. The detachable anchor head consists of three working strands and one reclaiming cable (releasing strand) (Fig. 4.3). The tapered wedge principle is used to tighten the reclaiming cable and the working cable. The axial force is transformed into a radial force, and the clamping force is applied to the anchor cable for the purpose of fastening as follows:

1. The inner anchor blocks (wedges) and the outer anchor ring are connected with the inner cones. The conical surface of the inner anchor block is matched with the cone face of the outer anchor ring and is adapted to the outer cone face of the clip between the force steel strand and the cone (Figure 4.2).
2. The clip and inner anchor block are split, and the number of internal anchor blocks is consistent with the number of working strands.

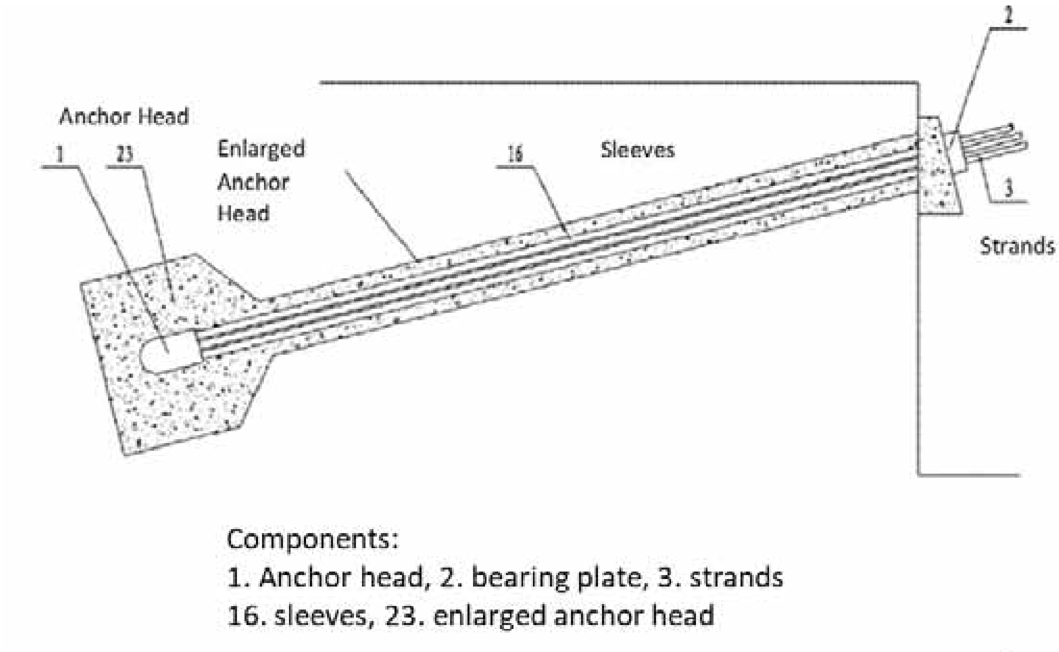


Fig. 4.1. Sketch of detachable anchor
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

Fig. 4.2. Detachable anchor head (the lower portion is a retractable pushing rod with grout injection port)
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.).

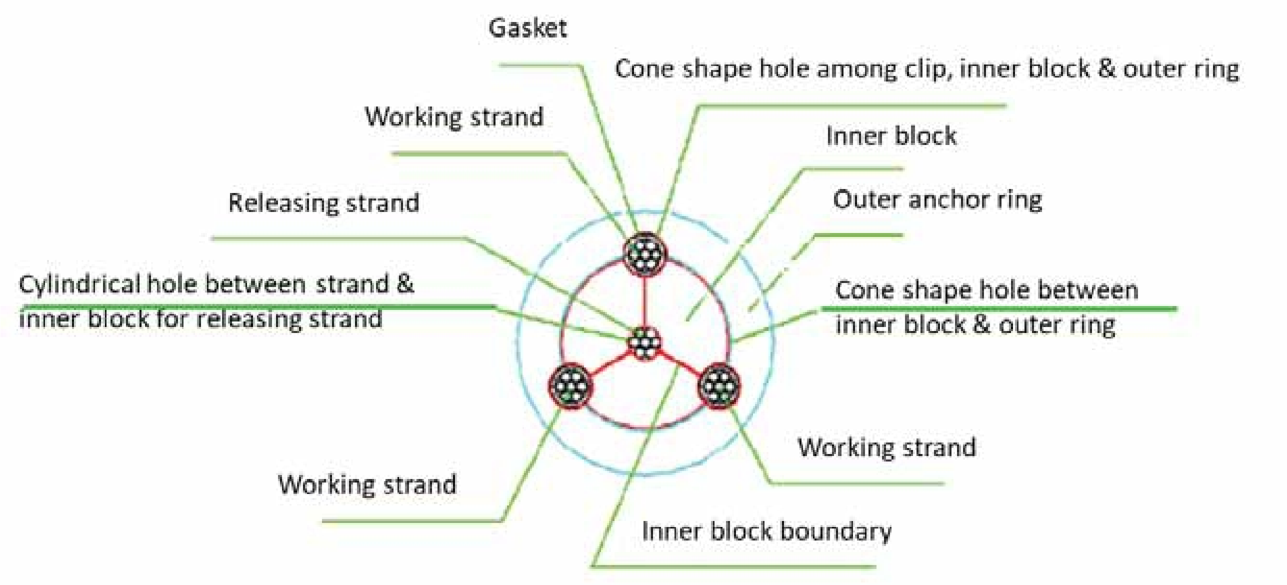


Fig. 4.3. Details of strands releasing parts
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

3. The central position of the inner anchor block is a cylindrical inner hole matched with the steel strand for releasing, and a steel stranded wire is clamped for recovery and unlocking in the cylindrical inner hole.
4. In releasing, only 2 to 3 tons of pulling force is applied to the reclaiming cable. After the reclaiming cable is extended about 100 mm (4 inch), the working steel strands can be released and pulled out by hand (Fig. 4.4).
5. The anchor strands release operation usually takes approximately 10 minutes.

Fig. 4.4. A mono jack pulling the reclaiming cable to release the locking wedges.

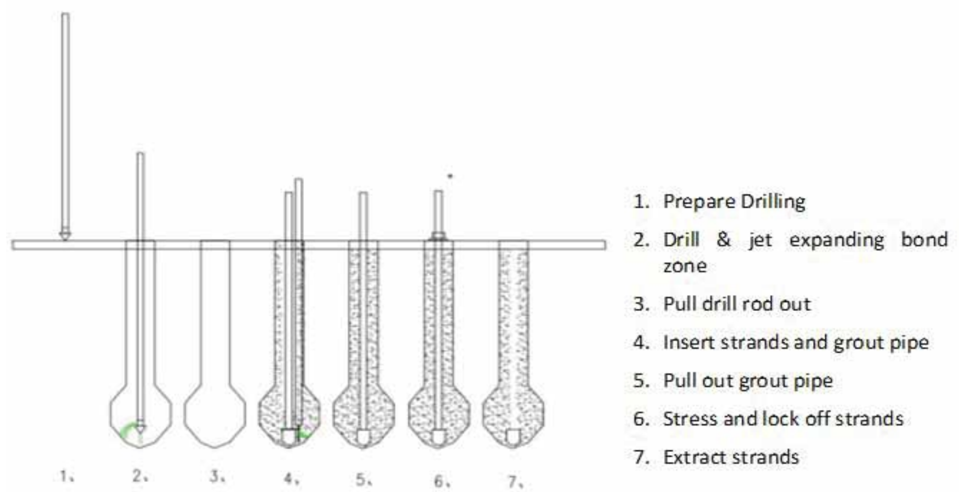
After the anchor strands are recovered, the anchor head is left in the ground, which is a small piece with minimum obstruction to future construction.

The detachable anchor installation process is shown in Figure 4.5. Depending on the soil properties, one of the three options can be selected.

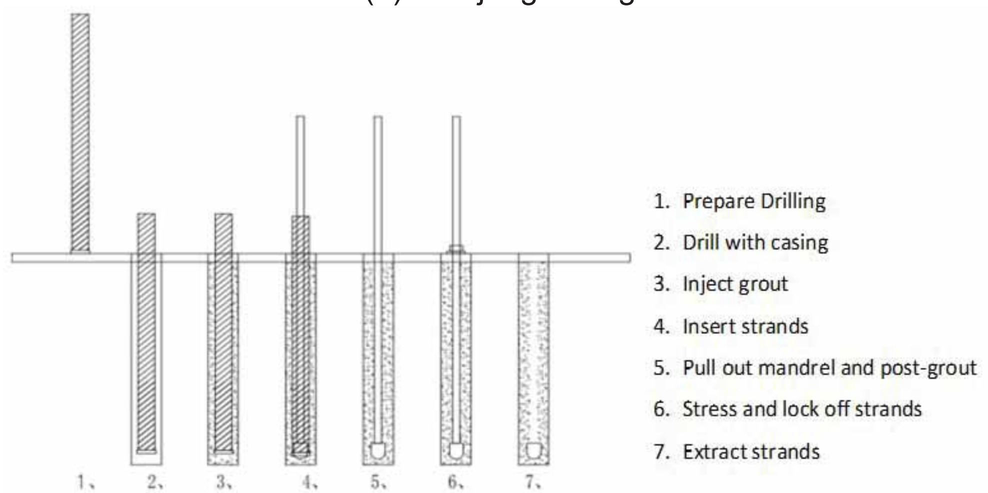
4.3 Case study of detachable anchor application

4.3.1 Project description

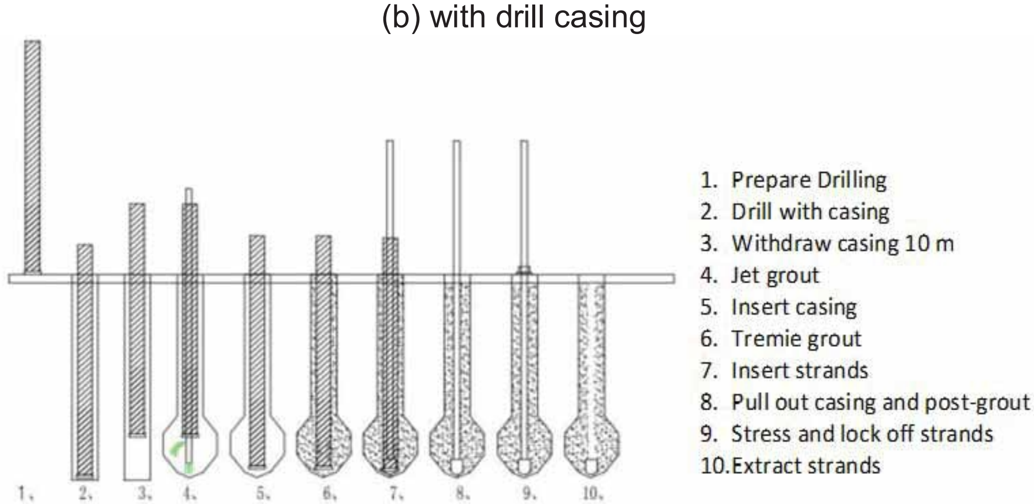
The scan tour team visited an excavation project site in Xiaoshan Sci-Tech City South District, Hangzhou, Zhejiang Province. The planned two-story basement excavation will reach a depth of 12 m (39 ft) in very difficult soils with the groundwater table at a depth of only 0.7 m (2.3 ft) below the ground surface. The excavation contractor is Zhengbang Water Power Construction Inc. of Zhejiang Province, and the detachable anchor supplier is Zhejiang Zhong Qiao Post Tension Equipment, LLC.



(a) with jet grouting



(b) with drill casing



(c) with drill casing and jet grouting

Fig. 4.5. Detachable anchor installation process
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

Fig. 4.6 shows that the excavation and earth retaining wall design considered the excavation depth, soil conditions and surrounding environmental restrictions, and used two layers of detachable anchors. Outside the excavation zone, the groundwater table was lowered using dewatering wells. Inside the excavation, sump pumps were prepared to reduce water level further, if needed. Table 4.1 provides the description of the soil layers in this project.

The earth retaining wall was constructed using multi-axis deep mixed (DM) columns. Each individual column was 1 m (3.3 ft) in diameter, overlapped into the adjacent columns, and was intended to cut off horizontal water flow into the excavation pit. In every other column, a wide flange beam was inserted to a depth of 24 m (79 ft). A reinforced concrete grade beam was constructed atop of the DM columns and was connected to the wide flange beams. The top layer of anchors were tied to the grade beam. It was observed that the wide flange beams were covered in a grease and tar mix, and the Team was informed that the beams would be pulled out after the building construction was finished for use on another future project.

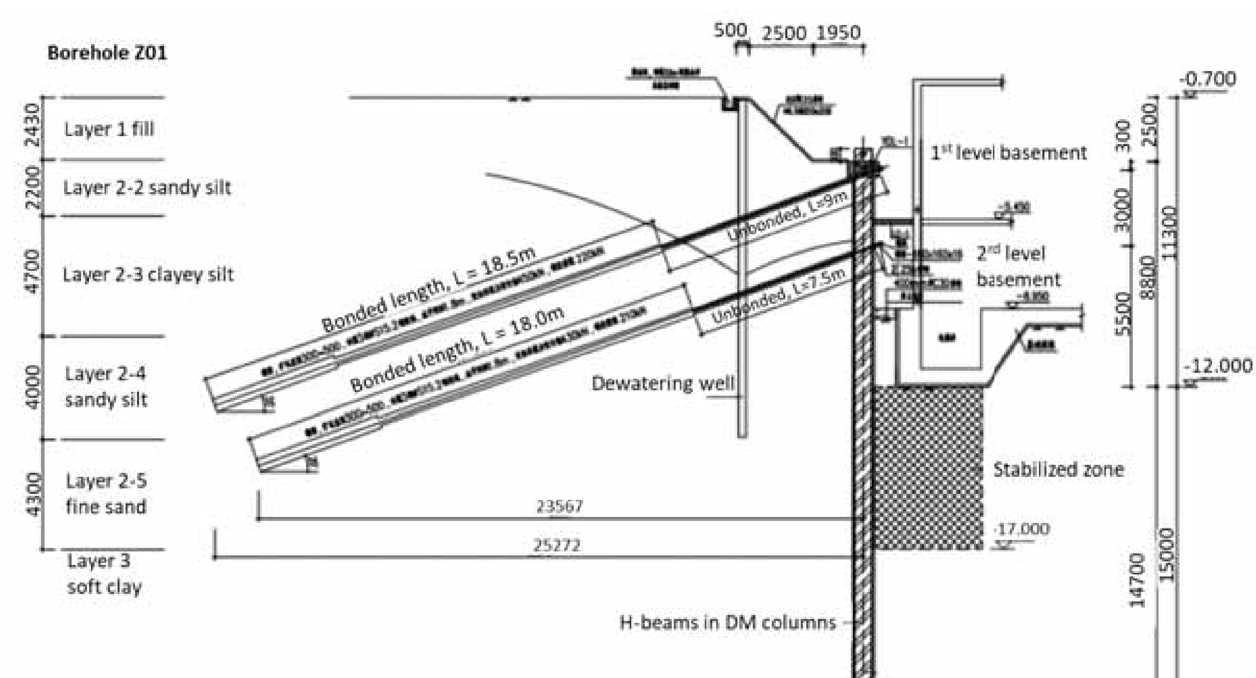


Fig. 4.6. Excavation and retaining wall cross-section
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

Table 4.1 Description of soil layers in this project
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

Layer No.	Description
Layer 1	Fill: Silt with roots, original building site with 0.2 m (8 inch) concrete paving overlay rubble and silts; original water pond site with organic sediment clays; 0.5 to 3.9 m (1.6 to 12.8 ft) thick, bottom depth 2.2 to 5.1 m (2.2 to 16.6 ft)
Layer 2-2	Sandy Silt: Grey, very wet, medium dense, minor mica content, sensitive to cyclic shaking, low plasticity, 0.9 to 2.9 m (3 to 9.5 ft) thick, bottom depth 0.33 to 2.76 m (1 to 9 ft)
Layer 2-3	Clayey Silt: Grey, wet, medium dense, contains mica, sensitive to cyclic shaking, 0.9 to 8.6 m (3 to 28 ft) thick, bottom depth 7.04 to 10.66 m (23 to 35 ft)
Layer 2-4	Sandy Silt: Grey, very wet, medium dense, in lenses, with mica, sensitive to cyclic shaking, 1.2 to 4.4 m (4 to 14 ft) thick
Layer 2-5	Fine Sand: Grey, saturated, medium dense, in lenses, with mica, 0.9 to 6.2 m (3 to 20 ft) thick
Layer 3	Plastic Clay: Dark grey, plastic, with organic, high dry strength, 16.8 to 21.1 m (55 to 69 ft) thick

Table 4.2 provides the parameters of the anchor drill as shown in Figure 4.7.

Table 4.2 Drilling Parameters
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

Item	Parameter
Hole diameter (mm)	150~250
Hole depth (m)	150~170
Drill casing diameter (mm)	73,89,102,114
Drill angle (Degree)	0~90
RPM	10,20,30,35,40,60,70,85,130,170
Motor power (KW)	55+18.5
Jet grouting pump	XPB-90 high pressure pump

Fig. 4.7. MDL-150D Anchor Drill
(source: Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and the Architectural Design and Research Institute of Zhejiang University Co., Ltd.)

4.3.2 Construction procedure

After the 180 mm (7 in) diameter anchor hole is drilled to the design depth, high pressure jet grouting is performed in the bottom 3 to 5 m (10 to 16 ft) of the anchor hole. The target diameter of the jet grouted anchor is 500 mm (19.7 in). Regular Portland cement at a water-to-cement ratio of approximately 0.8 is used for the grout mix, which results in a compressive strength of approximately 2.5 MPa (365 psi). The amount of cement used is 50 to 60 kg per linear meter (34 to 40 lb per linear ft) of jet grouting. The injection pressure of the rotary jet expansion is 15 to 20 MPa (2,175 to 2,900 psi) throughout most of the anchor, but is reduced to less than 5 MPa (725 psi) in the unbond zone. This installation procedure is similar to that illustrated in Figure 4.5(a).

The anchor uses 15.2 mm (0.6 in) diameter, 7-strand wires with an ultimate strength of 1,860 MPa (270 ksi) to form the strand. In both the bond zone and the detachable end zone, each strand is covered with corrosion protection grease and a plastic sleeve. The top anchor plate is 150 mm (6 in) in diameter and 20 mm (0.8 in) in thickness.

4.4 Research work and key findings

The detachable anchor system was developed by a Chinese construction company, Zhejiang Zhongqiao Prestress Equipment Co., Ltd. and obtained a Chinese patent. The engineer from Zhejiang Zhongqiao Prestress Equipment Co., Ltd told us that they tried many different ways to develop a strand releasing mechanism, including strand loops, threaded locking wedges, and, ultimately, this unique detachable anchor system.

Combining a soil anchor with jet grouting can significantly increase the anchor geotechnical bond capacity. The anchor/soil bond interface is enlarged by the jet grouted soilcrete, which can increase the anchor capacity even in medium stiff clay zones.

4.5 Identified innovations

The Chinese detachable anchor system release mechanism is different from other detachable anchor systems developed in South Korea and in North America. The reusable wide flange steel beams in the deep mixed columns further reduce construction cost and environmental impact. The beam is coated with a tar and grease mix, and vertically inserted into the fresh mixed column. Above the deep mixed column, the beam is wrapped with Styrofoam sheets and cast into a concrete grade beam. The overlapped deep mixed columns, reinforced by wide flange beams, and detachable anchors connected to the grade beam, are combined to form a retaining wall in soft ground with a shallow groundwater table depth as shown in Figure 4.8. After the excavation project is finished, both the anchor strands and the wide flange beams are removed.

Fig. 4.8. Reusable wide flange beams and detachable anchors in an earth retaining wall in Xiaoshan Sci-Tech City South District, Hangzhou, Zhejiang Province.

4.6 Lessons learned and recommendations

The scan tour team really appreciates that the Chinese colleagues decided to share their knowledge and experience with their detachable anchor system. We can adopt the Chinese reusable anchor strands and wide flange beams approach in North America to reduce our construction cost and environmental impacts.

5. DEEP SOIL MIXING

5.1 Introduction

This section summarizes a site visit on May 25, 2018 to a Deep Soil Mixing (DSM) project in Deqing, Zhejiang, China and a review on technical documents complied during and after the scan tour about the research and development of DSM technology and its field applications in China.

5.2 Description of the technology

Deep Soil Mixing (DSM or DM) is a ground improvement technology that mixes existing soil with cementitious binders using mixing shafts consisting of auger cutting heads, discontinuous auger flights, and mixing paddles. The mixing tool varies from single to eight-shaft configurations depending on the purpose of ground improvement. The most frequently used binders are Portland cement and slag cement. The binder can be blended with in situ soil in either wet or dry form. The soil-cement mixture generally has higher strength, less compressibility and lower permeability compared with the native soils. In the U.S. the applications are to increase bearing capacity, reduce settlement, and increase the lateral shear resistance for slope stability. It is also often used for seismic upgrade for foundation of infrastructures including liquefaction and lateral spreading mitigation. In China, DSM was extensively used to improve the soft ground under roadway embankments to provide bearing capacity and control settlement.

5.3 Site Visit – Ground Improvement for Hangzhou Beltway at Deqing, Zhejiang Province

5.3.1 Project description

The project of the western multiple line of Hangzhou Beltway at the Huzhou Section 2 is located in Deqing county, Zhejiang Province, which is designed as a two-way six-lane highway with a speed limit of 100 km/h (62 mph). The total length of the highway at this section is 50.8 km (31.6 mi), as shown in Fig. 5.1, with a 32.5-km (20.2-mi) long section to be constructed over soft soil. The general embankment heights vary from 2 to 6 m (6.6 to 19.7 ft), and the heights of bridge-approach embankments vary from 5 to 6 m (16.4 to 19.7 ft). The project site is in a plain river network area of Hangjia Lake. The soft soil has a thickness of 2 to 44 m (6.6 to 144.4 ft). The properties of the soft soil are shown in Table 5.1.

Fig. 5.1. Layout of the western multiple line of Hangzhou Beltway (source: Zhejiang Communication Investment Group Co., Ltd.)

Table 5.1 Properties of soft soil
(source: Zhejiang Communication Investment Group Co., Ltd.)

Layer	***w*** (%)	***e***	***E*s** MPa (psi)	**C** kPa (psf)	***Φ*** (°)
Soft soil 1	43.5	1.198	3.07 (445)	9.8 (205)	4.6
Soft soil 2	40.9	1.167	3.23 (470)	10.3 (215)	5.3

Note: w = water content, e = void ratio, E_s = constrained modulus, c = cohesion, and ϕ = friction angle. Total strength (c and ϕ) is commonly used in design in China.

5.3.2 Ground improvement techniques

Based on the variation of embankment height and soft soil thickness, various approaches are used to improve the soft soil.

- Deep mixing method

Mixing tool with single-directional rotation is used to improve the area with soft soil less than 10 m (33 ft) in depth and mixing tool with bi-directional rotation is used to improve the area with soft soil greater than 10 m (33 ft) in depth. The mixing tool with single-directional rotation as shown in Fig. 5.2(a) is the conventional equipment used in China. The two shafts were assembled to penetration simultaneously for production purpose and there is no mixing interaction between these two mixing shafts. The mixing tool with bi-directional rotation as shown in Fig. 5.2(b) is a single shaft mixing tool with concentric counter-rotating double tubes developed to improve the quality of the soil mixing column, especially deeper columns. The research and development of the bi-directional rotation mixing tool is presented in Section 5.4 Innovations. The internet real-time monitoring and data management system is used to monitor the whole construction process of soil mixing columns. More detail about the internet monitoring and data management system is also presented in Section 5.4 Innovations.

(a) (b)

Fig. 5.2. DSM Mixing Tools (single and bi-directional rotation types)

- Geosynthetic-reinforced pile supported (GRPS) embankment

Bamboo shaped pre-stressed hollow concrete piles are used with a cast-in-place pile cap (1.0 m ×1.0 m × 0.35 m) (3.3 ft x 3.3 ft x 1.1 ft) on the pile head and a single layer of geogrid over the pile caps. Details of bamboo shaped pre-stressed hollow concrete piles will be presented in Section 7 of this report.

- Surface soft soil stabilization

The soft clay near the ground surface is stabilized by the surface mixing using cement slurry. This shallow surface soil mixing produced a stable working platform for the performance of deep soil mixing and installation of bamboo shaped hollow concrete piles. Section 6 of this report presents details of the surface soft soil stabilization.

5.3.3 Ground improvement plan

Ground improvement technologies used at this project site include deep mixing and geosynthetic-reinforced pile supported embankments. The selection of ground improvement methods is based on the embankment height, H, and thickness of soft soil to be treated, D. In the area with soft soil at surface, the surface soft soil stabilization is used to construct a working platform for the deep mixing and GRPS equipment to operate.

- Bridge-approach embankment

  (1) At H<3 m (10 ft) and D<20 m (66 ft), deep mixing method

  (2) At H>3 m (10 ft) and D>20 m (66 ft), GRPS embankment

- General embankment

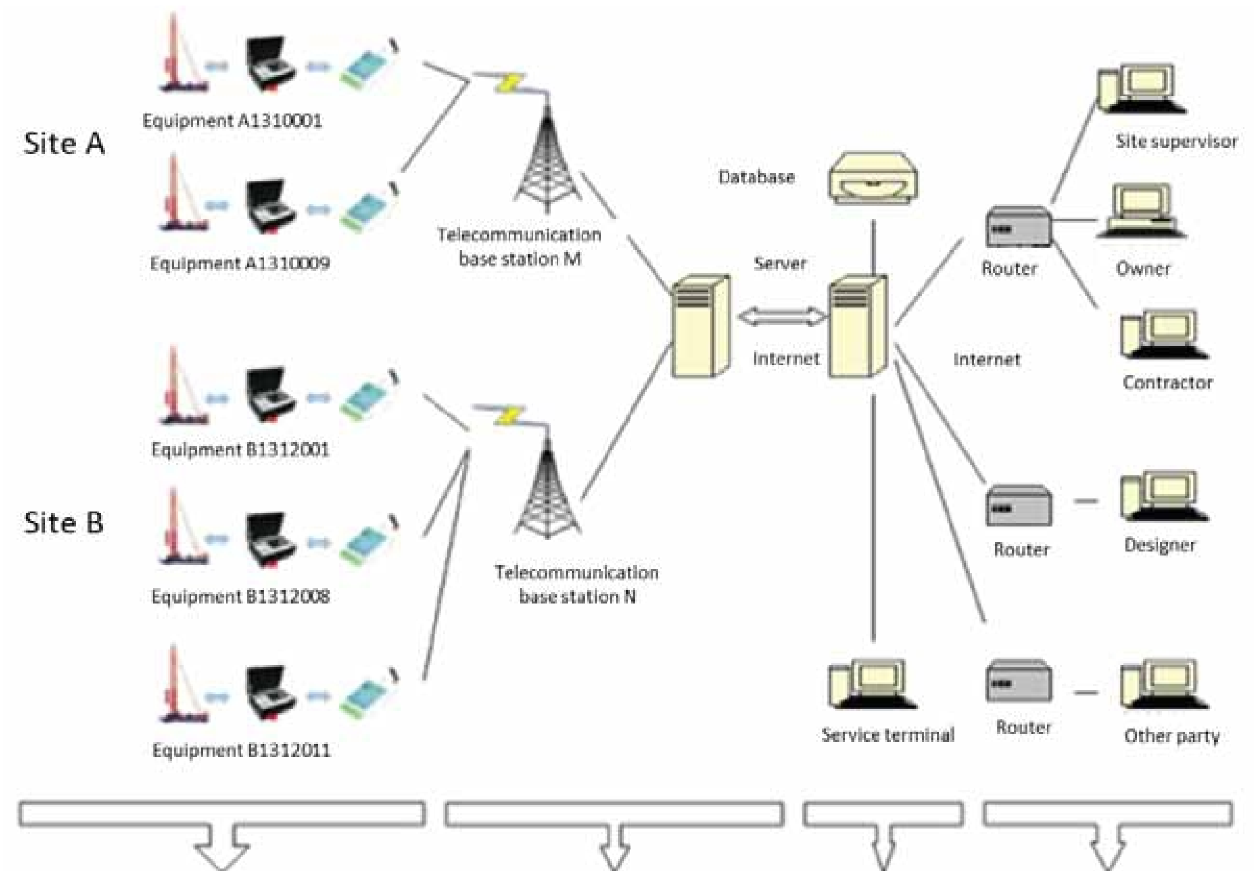
  (1) At 2 m (7 ft) < H < 5 m (16 ft), deep mixing method

  (2) At H>5 m (16 ft), GRPS embankment

5.4 Innovations Identified

5.4.1 Internet real-time monitoring and data management system

Using existing internet technologies and sensor technologies, a real-time monitoring and data management system was developed for the quality control and construction management of the deep mixing operation. The system is divided into software part and hardware part. The hardware part includes various types of instruments for real-time monitoring and the software part is composed of subsystems including mainly signal reception, data sorting, comprehensive analysis and results feedback. The hardware and software are connected in real-time through internet. The whole system includes the following four main parts as shown in Fig. 5.3:



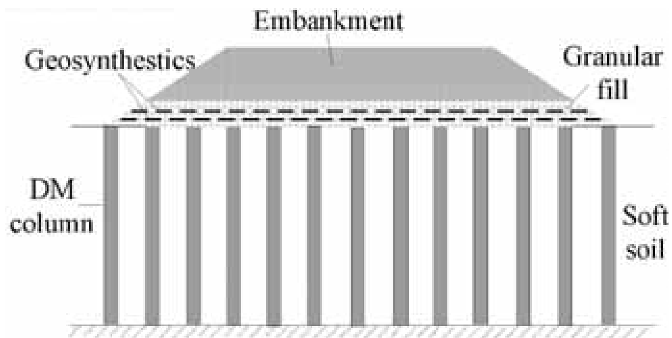
Field Data Acquisition Signal transmission system Supervision center Client remote monitoring

Fig. 5.3. Internet real-time monitoring and data analysis system
(source: Zhejiang Transportation Co. Testing Technological Company)

This system monitors the parameters affecting the quality of deep mixing column installation and generates data report that can be accessed at any time for comprehensive evaluation of the construction process and quality control by the design, construction, monitoring and management team. It eliminates/reduces human error or interference and provides real-time details (e.g., penetration depth and rate, grout flow rate, and electrical current) and credible data basis for the deep mixing construction operation, quality control, quality assurance, and final project evaluation.

5.4.2 Equipment innovation

Deep soil mixing columns are widely used to support highway and railway embankments on soft ground in China as illustrated in Fig. 5.4. The diameter of DM column generally is 0.5 m (1.6 ft) and the spacing between DM columns varies from 1.0 m (3.3 ft) to 1.5 m (4.9 ft). A load transfer platform consisting of geosynthestic-reinforced granular fill or soil-cement slab is needed to transfer the embankment load to DM columns and reduce the differential settlement at ground surface. However, the close spacing between DM columns and the load transfer platform increase the construction cost. A series of research and field tests were carried out under the direction of Dr. Songyu Liu of Southeast University, Nanjing, China to develop new deep mixing equipment to solve the problem and also to reduce the overall cost of DM column construction. Details of the development of new equipment to install DM columns are presented in Section 11.



Firm soil or bedrock

Fig. 5.4. Deep mixing columns-supported embankment

5.5 Lessons learned and recommendations

Internet real-time monitoring and data management system could use existing internet technologies and sensor technologies to improve the quality control/quality assurance by the deep mixing contractors and owner's representative. It could provide real-time monitoring for early detection of construction difficulties or deficiencies and provide data for efficient construction management of the deep mixing operation.

The concentric counter-rotating double tubes mixing tool improves the quality of deep mixing column.

5.6 Summary

This section summarizes the site visit to a Deep Soil Mixing project in Deqing, Zhejiang Province, China and a review of technical documents complied during and after the scan tour. Deep soil mixing and geosynthetic-reinforced bamboo shaped hollow concrete piles were used to support a 32.5-km (20.2 mi) long section of embankment to be constructed over soft soil. The back hoe mounted shallow soil mixing equipment was used to stabilize the near surface soft soil to produce a stable working platform for the installation of deep mixing columns and bamboo shaped hollow concrete piles. Internet real-time monitoring and data management system was used to improve the quality control/quality assurance and to provide data for efficient construction management of the deep mixing operation.

6. SURFACE SOFT SOIL STABILIZATION

6.1 Introduction

When the surface soil is very soft, consisting mainly of soft clay, shallow soft soil stabilization technology (also called surface mass stabilization) is used to increase soil strength and modulus. Generally, cement and/or fly ash are used for shallow mixing of soft soil. The shallow mass soil mixing method was used to provide a working platform to achieve minimum bearing capacity for the machinery or equipment for other ground improvement technologies.

6.2 Description of the Technology

Grout consisting of a mixture of water and binder (cement and fly ash) is pumped into and mixed with in-situ soil using a soil mixing tool. After mixing is completed, the surface is smoothened using an excavator. Surface soil mixing stabilization helps the soft ground to form a hard crust with increased modulus and strength. The soil improvement with cement and fly ash is mainly attributed to cement hydration and pozzolanic reactions. Surface stabilization provides a stable working surface for piling construction or other ground improvement technologies. The stabilized surfaces are ideally suited for the construction of parking lots, roads, docks, airfields, and industrial amenities.

The advantages of surface stabilization include quick process, environment friendly, no excavation required, no fill and cut required, and minimal site disturbance.

6.3 Project Site

The site that was visited was an ongoing project for the construction of a highway over soft soil at Deqing, Zhejiang Province. This section of the highway is 50.8 km (32 mi) long, with a 32.5-km (20 mi) long section over soft soil. The height of the embankment varies from 2 to 6 m (6.5 to 19.5 ft). The soft soil consists of lacustrine deposits, classified as mainly as silty clay with the thickness ranging from 2 m to 44 m (6.5 to 144 ft).

Ground improvement technologies including deep mixing and geosynthetic-reinforced pile supported (GRPS) embankments are used to improve the soft soil. For the area with soft near surface soils, accessibility of construction equipment is a major concern. Therefore, surface soft soil stabilization was used to develop a working platform for machinery and equipment for piling installation and deep mixing. A large amount of surface mass stabilization has been used for soft ground improvement.

Properties of soft soil in the project site are summarized in Table 5.1. For the surface stabilization equipment used in this project site, the soil should have a moisture content less than 60%. In this case, grout was used to facilitate the mixing and to achieve a relative uniform mixture. However, for a much higher moisture content, the soil may be mixed directly with dry binder, which would require different mixing equipment. In this project, the grout had a water-binder ratio of 0.5 to 0.7 and the binder included 3.0% wt.

of Portland cement (28-day grout compressive strength of 42.5 MPa (6,164 psi)) and 3.0% wt. of fly ash (Class F) per unit weight of soft soil.

6.4 Specification of Surface Soil Mixing Equipment

The equipment consists of a mixing machine comprising a mixer attached to an excavator, and a binder supply system (Fig. 6.1).

(1) Mixer: the operation parameters are summarized in Table 6.2.

(2) Excavator: model 240 or higher (i.e., 24 tons or larger).

(3) Binder supply system (Fig. 6.2): it mixes cement, fly ash, and water to produce grout.

Table 6.2 Parameters of the soil mixer used

(source: China Railway Construction Co. Ltd.)

Mixing machine	Unit mixing area 1 sq m (10.8 sq ft) Length = 1300 to 1800 mm (51 to 71 inch) Width = 1300 to 1800 mm (51 to 71 inch) Height = 800 to 1000 mm (31 to 39 inch)
Production rate	50 to 80 cu m/ hr (1,765 to 2,825 cu ft/hr)

(a) (b)

Fig. 6.1 Mixing machine: (a) excavator-based mixing machine and (b) horizontal drum mixer

Fig. 6.2. The binder or grout supply system

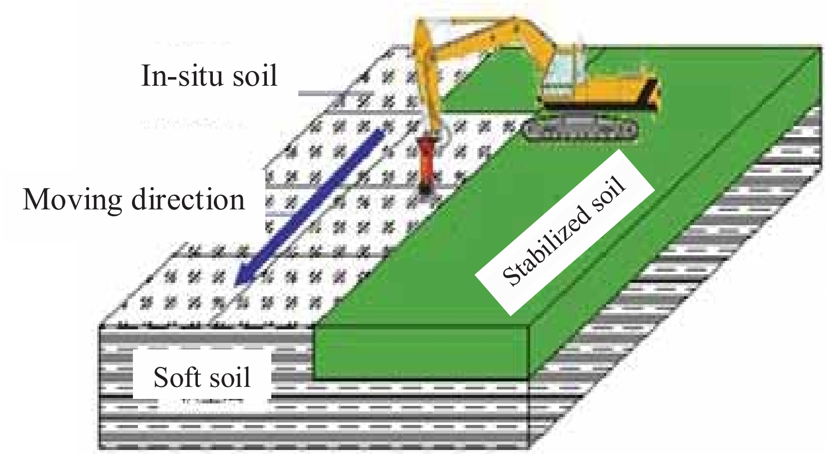
6.5 Process of Mixing

At first, a grid pattern of approximately 3 m × 3 m (10 ft by 10 ft) was marked using lime for grout injection as shown in Fig. 6.3.

(a) Making grids (b) Soil mixing

Fig. 6.3. Marking grids for shallow soil mixing and ready for soil mixing

The mixing followed the left-right and front-back sequence, as illustrated in Fig. 6.4a. At each specific position, the mixer was moved downward and upward to blend the soil with the binder (Fig. 6.4b) as grout was drawn from the feeder and injected (Fig. 6.4c) into the soil and to ensure uniform mixing. In general, a 5-cm overlap was used to ensure complete coverage and a 2% slope was adopted so that no water would accumulate on surface.



(a) Treatment sequence (source: China Railway Construction Co. Ltd.)

(b) Tooling movement in the soil (c) Grout injection from the mixing tool

Fig. 6.4. Surface soil mixing

After the shallow soil mixing was completed, the surface was leveled off (Fig. 6.5) and was left to cure. The treated soil normally took from 7 to 14 days to cure before construction equipment for other ground improvement could be mobilized on the stabilized surface. Minimum curing periods of 7 days and 14 days were specified to achieve the minimum strengths necessary to support a working platform for deep mixing construction and for the construction of pre-stressed concrete piles, respectively.

Fig. 6.5. Final surface of shallow soil mixing prior to curing

6.6 Lessons Learned and Recommendations

An ongoing project site with surface mass stabilization was visited. The surface mass stabilization was used to provide a working platform for deep mixing and pile driving to improve soft soil for highway embankment construction. The technique used in the project site was only suitable for soft clay with moisture content less than 60%. Quality control was relatively difficult and mainly established based on the experience of the contractor. To achieve the minimum bearing capacity of the working platform, a minimum waiting period of 7 days or 14 days was recommended prior to the construction of deep mixing and pile driving, respectively.

7. BAMBOO-SHAPED PILES

7.1 Introduction

The bamboo-shaped or nodular pipe piling system (static drill rooted nodular [SDRN] pile system) is a composite system that combines pile foundations with soil mixing and grouting. At the completion of the work, a piling element is constructed within a partially grouted and partially soil mixed hole. This type of piling system has been used for structural support of structures and in conjunction with column-supported embankments.

In general, a precast, pre-stressed concrete pile is fabricated using a high-speed centrifugal casting process, which results in a dense concrete matrix and a smooth surficial finish. In addition, because of centrifugal process, a concrete mix with a lower water/cement ratio than is typically used in the pre-casting of concrete piles, which makes the pile hydrophilic. As such, after the piling is installed into the ground, the hydrophilic pile slowly absorbs the free water in the soil surrounding the pile, which ultimately increases the adhesion (i.e., side friction) between the soil mix ground and the concrete pile.

Practitioners have reported an increase in side and base resistance, a decrease in drill spoils, and improved performance when using this type of foundation system compared to conventional cast-in-place bored piling. As reported by Zhou et al (2015), using the SDRN system on a power station project resulted in cost saving of approximately 10% along with a disposal volume of drill spoils of less than 40% as compared to conventional cast-in-place bored piles. This method appears to be specific to the Chinese (and/or Asian) marketplace and has not been utilized in this manner in North American engineering and construction practices.

7.2 Piling Geometry

Typical diameters of the precast concrete elements range from approximately 500 to 800 mm (20 to 31 in), and there appears to be two predominant styles that are utilized for nodular piling (Fig. 7.1a). One style uses multiple ribs or protrusions at relatively equal spacing along the length of the pile to provide additional bearing area to resist axial loading. The second style uses a smooth surface area with one or few indentions along the length of the pile.

Each of the concrete piling segments are manufactured in a fabrication facility prior to arrival onsite. As such, there are limitations to the lengths to which these precast, prestressed concrete piles can be made. To achieve long piling lengths, the ends of the individual piling segments are fabricated with tapered ribbed inserts (Fig. 7.1b) into which ribbed dowels can be inserted prior to the attachment of additional piling segments.

(a) nodular pile segments

(b) Tapered ribbed inserts at the ends

Fig. 7.1. Nodular piles

7.3 General Construction Process

The general construction process of this foundation system is summarized as follows:

- At each piling location, the soil is pre-bored to the desired piling depth (but the soil not completely removed from the bore). The diameter of the pre-bore was stated to be at least 100 mm (4 in) greater than the diameter of the precast piling element.
- Once the desired depth has been reached, the diameter of the bore hole near the base of the pile is increased using specially designed tooling (up to about 4 to 5 times the diameter of the precast piling).
- After enlarging the diameter at the base of the pile, grout (water/cement ratio (w/c) around 0.6 to 0.9) is introduced into the pre-bored hole near the base, where the auger/tooling mixes the grout with the in-situ soil near the base and within the expanded zone.
- As the tooling is withdrawn from the pre-bored hole, grout with a higher w/c (around 1.0 to 1.5) is used to mix the soil along the remaining length of the foundation element.

- After the tooling is extracted, the precast piling is inserted into the soil mixed hole under its self-weight.

7.4 Project Visit - Western Line of the Hangzhou Beltway Project in Deqing

One project site was visited in Deqing, Zhejiang Province, where multiple techniques were being utilized for the construction of the Hangzhou Beltway project. At the time of the scan tour, no work on the nodular piling system was being performed. The brief description of this project is also provided in Section 5.3.1.

7.4.1 Project Scope

Different ground improvement or foundation techniques were used at this site based on the height of the embankment that was to be constructed and on the thickness of the soft soils below the embankment sections, as discussed in Section 5.3.3.

For taller earth structures, geosynthetic-reinforced pile supported (GRPS) embankments with bamboo-shaped prestressed hollow concrete piles (Fig. 7.1) were to be used along with a cast-in-place pile cap atop each of the bamboo-shaped piles. The pile cap measured 100 cm by 100 cm by 35 cm thick (39 in by 39 in by 13.75 in thick). A single layer of geogrid was to be placed over the top of the pile caps to assist in distributing the load imposed by the embankment fill and loading. In some instances, when required due to its very soft consistency, the muddy soil near the ground surface was to be stabilized using surface soil mixing incorporating a simple cementitious slurry as described in Section 6.

7.4.2 Equipment

The equipment used to construct this piling system is rather straightforward, excluding the centrifugal operation used to fabricate the precast concrete piles. To pre-bore, expand the base, and soil mix the hole, a specially-designed tool (e.g., auger, drill teeth, and expander) is used; however, at the time of the site visit, a tool was not available onsite nor was the scan tour provided with a photograph of such a tool. The setup used to produce the grout mixture is the same setup (i.e., cement silo, mixer, agitator, pump, etc.) that was used to produce the grout used for the deep or shallow soil mixing operations. The piling rig used to install the precast concrete bamboo-shaped piles (Fig. 7.2) is relatively unsophisticated compared to typical piling rigs. Since the bamboo-shaped piles are installed using their self-weight with no impact or vibration, the main functions of the piling rig are to move, hoist, and position the piling segments into proper alignment.

(a) (b)

Figure 7.2. Photographs of the piling rig used to install the bamboo-shaped precast concrete piles

7.5 Research Work and Key Findings

This composite system combines bamboo-shaped or nodular precast concrete piling elements with soil mixing and/or grouting. For the project site visited in Deqing, the piling system was being used as a ground modification technique for earth embankments (i.e., column-supported embankments). This method has not been utilized in North American engineering and construction practices but has been used in China and Japan construction practices.

The key observations made for this piling system and project include:

(1) Using a high-speed centrifugal casting process, the concrete mix has a lower water/cement ratio than is typically used in the pre-casting of concrete piles, which results in a pile of high quality and dense concrete matrix.
(2) Lightweight and relatively unsophisticated equipment can be used with this system as the piling segments are modular (connected using dowels to increase the overall length) and the installation relies on the self-weight of pile without external impact or vibration.
(3) Using the composite system has resulted in both cost savings and volume of material disposal along with an increase in side and base resistance.

7.6 Lessons Learned and Recommendations

Research studies have been published on the nodular piling system, load transfer mechanism for axial loading, and behavior of this piling method with and without caps at the top of the piles (sometimes used in column-supported embankment systems). A literature review of available studies and case histories would be beneficial for understanding the fundamental mechanisms (e.g., material behavior during/after casting, soil/structure interaction, in-situ soil/mixed soil/structure interaction, load transfer, behavior at the joints, etc.) associated with this method. As conveyed by the contractors performing the work on the project site, the method appears to be effective in soft soil conditions.

8. VACUUM PRELOADING

8.1 Introduction

Preloading is a commonly used ground improvement technique to increase strength and stability of soft clays and reduce post construction settlement. Preloading is typically performed by placing fill material over the area of improvement. The stresses induced by the weight of the fill material cause the soil to consolidate. In lieu of relying on the weight of fill material, preloading can be also be induced with application of vacuum. Vacuum preloading offers several advantages over the conventional preloading by fill, such as eliminating the need for fill material and heavy construction equipment, and reducing the risk of soil bearing failure due to the relatively uniform stresses introduced in the soil mass during vacuum preloading.

This section of the report presents an overview of the vacuum preloading process and a summary of observations during the site visit by the scan tour team to a site in Taizhou, Zhejiang Province, China where different vacuum preloading techniques are being tested and used for a large ground improvement project for a development over reclaimed land. Besides the techniques witnessed during the site visit, the recent advances of the vacuum preloading techniques in China that we learned from the second China-US workshop are discussed.

8.2 Description of Vacuum Preloading Process

In principle, soil consolidation by vacuum preloading is the same as vacuum sealing of food for preservation. The atmospheric pressure on the earth surface is approximately 100 kPa (14.7 psi). By sucking the air and water out of a sealed soil mass and maintaining the vacuum for a period of time, the soils are subjected to a vacuum-induced pressure and forced to undergo consolidation. Field studies have shown that approximately 70% of an ideal vacuum can be achieved on project sites to mimic approximately 3 m (10 ft) of surcharge. The typical setup of vacuum preloading is illustrated in Fig. 8.1. It consists of (1) a sand blanket that is used as a working platform, (2) prefabricated vertical drains (PVDs) installed to the depth of improvement, (3) horizontal vacuum tubes connecting the PVDs to vacuum pumps, (4) an impervious membrane, (5) vacuum pumps that induce negative pressures, drawing the water out of the ground through the PVDs and horizontal tubes, and (6) a peripheral ditch that collects water from vacuum preloading.

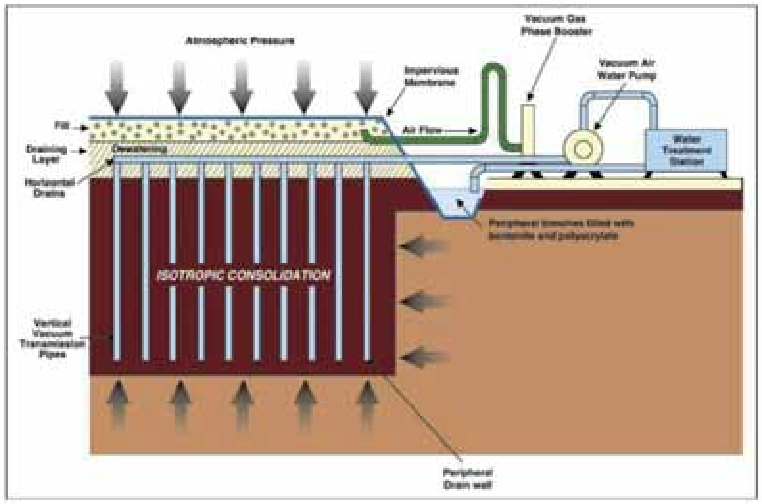


Fig. 8.1. Typical setup of vacuum preloading (Menard 2001)

8.3 Use and Recent Advances of Vacuum Preloading in China

Vacuum consolidation or vacuum preloading of soils was first introduced by Dr. W. Kjellman in 1952. Many researchers and engineers around the world have contributed to the improvements in the theoretical understanding and practices of the technology. However, vacuum preloading was seldom used until the 1980s when geosynthetic materials became popular and readily available for construction. China, however, has used the technology on numerous sites especially in the coastal regions where soft clay deposits are prevalent, such as in the Yangtze River Delta and the Pearl River Delta. In the U.S. vacuum consolidation is seldom used due to labor and energy costs as well as the lack of suitable sites with continuous soft soil layers without sand seams. Such was the case in a test program performed in the late 1980s at the port of Los Angeles (Jacob et al. 1994). North America seldom consolidates clays in river deltas.

Vacuum preloading has been successfully used on sites where improvement of soft homogeneous soils are needed. This technology is most effective and cost-efficient for large sites for highway embankments, railroads, airports or storage yards, such as container ports or bulk storage facilities.

Vacuum preloading eliminates the concerns associated with hauling, handling, and stockpiling large quantity of fill material. It can also reduce the risk of soil bearing failure due to the concentrated piling of fill materials. However, the traditional vacuum preloading technology also suffers several disadvantages, such as cracks on the ground (Fig. 8.3a), formation of soil columns around the PVDs (Fig. 8.3b), clogging in the PVDs by fines (Fig. 8.3c), bending of PVDs during installation (Fig. 8.3d), and shrinkage of vacuum tubes resulting in loss of vacuum pressures (Fig. 8.3e). Also critical is the loss of vacuum head due to membrane failure, membrane seal failure or a granular layer, aquifer, or a draw down that causes the vacuum to pull air.

(a)

(b) Cai (2018)

(c) Lei (2018)

(d) Lei (2018)

(e) Lei (2018)

Fig. 8.2. Shortcomings of vacuum preloading

To cope with the above-mentioned limitations, researchers and engineers in China have developed new techniques to improve the efficiency of vacuum preloading and to allow it to be used at sites with special challenges. These new improvements can be summarized in the following four categories:

(1) PVDs: New PVDs were designed to incorporate specialized filter fabric to resist clogging (Cai et al. 2018; Zheng et al. 2017) or more rigid core to prevent bending and maintain water flow inside the PVDs (Cai et al. 2018);

(2) Vacuum pumps: Electric pumps are more commonly used than diesel pumps. More powerful and centralized pumps are used in recent projects that were proven to be more efficient than many smaller water-jet vacuum pumps. The new vacuum pump design also included separation of air and water within the pump to improve efficiency (Zheng et al. 2017);

(3) Connections between PVDs and vacuum tubes: Different connections were designed and experimented to improve the speed of installation and efficiency of operation (Cai et al. 2018).

(4) The following four processes have been adopted in practice:

a. A multiple stage vacuum process that includes vacuum preloading on hydraulic fill to form a working platform followed by vacuum preloading on soils was successfully used for sites with extremely weak soils, like sludge or dredged mud (Zheng et al. 2017).

b. The combination of vacuum and air sparging was used to improve the effectiveness of vacuum preloading (Cai 2018; Lei 2018). As shown in Fig. 8.3, air booster PVDs are installed between the vacuum PVDs to inject air increasing the pressure gradient in soils between booster PVDs and PVDs in addition to the vacuum. This setup helps reduce the risk of clogging in PVDs and formation of soil columns.

c. The vacuum preloading with chemical modification was also employed to accelerate the consolidation in soils. Cai (2018) utilized lime to pretreat the dredged materials for short-term and long-term benefits. The short-term flocculation helps aggregate fine particles, increasing soil permeability and thus consolidation rate and the long-term pozzolanic reaction increases the soil strength.

d. The synchronous and alternated preloading method was developed, which is novel in the PVD installation pattern with varying PVD lengths and orientations in soils (Lei 2018) as illustrated in Fig. 8.4.

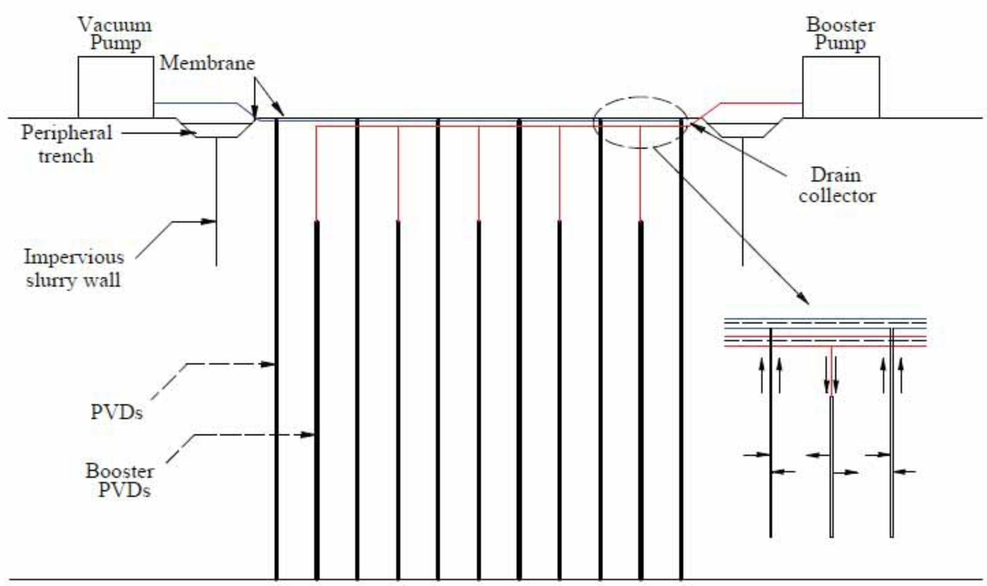
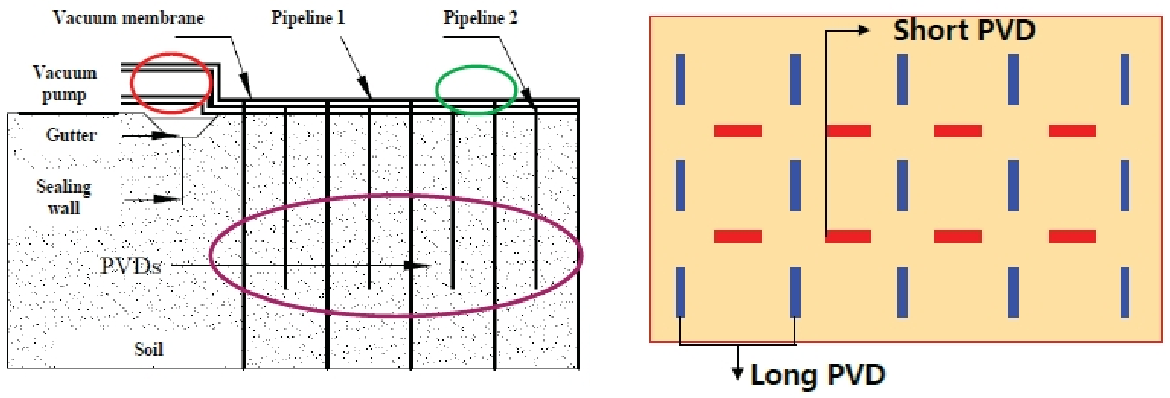


Fig. 8.3. Schematic of combined vacuum preloading and air sparging setup (Cai et al. 2018)



(a) (b)

Fig. 8.4. Schematic of synchronous and alternated vacuum preloading method: (a) cross sectional view and (b) plan view (Lei 2018)

8.4 Project Site and Subsurface Conditions

The project site is located east of the coastal city of Taizhou in Zhejiang Province, China. The site is part of a large reclaimed land (2.53 km^2 or 624 acres) for new developments that will include roads, buildings, airport runways, and parking space, as shown in Fig. 8.5. The scan tour team visited the zoomed-in treatment site of 2.53 km^2 (624 acres). The dredged fill, 3 to 10 m (10 to 33 ft) in thickness, is composed of silts and clays with a natural moisture content of 50 to 80%. The native soils underlying the dredged fill are mostly alluvial deposits of silts and clays with high natural moisture content in the range of 30 to 70%.

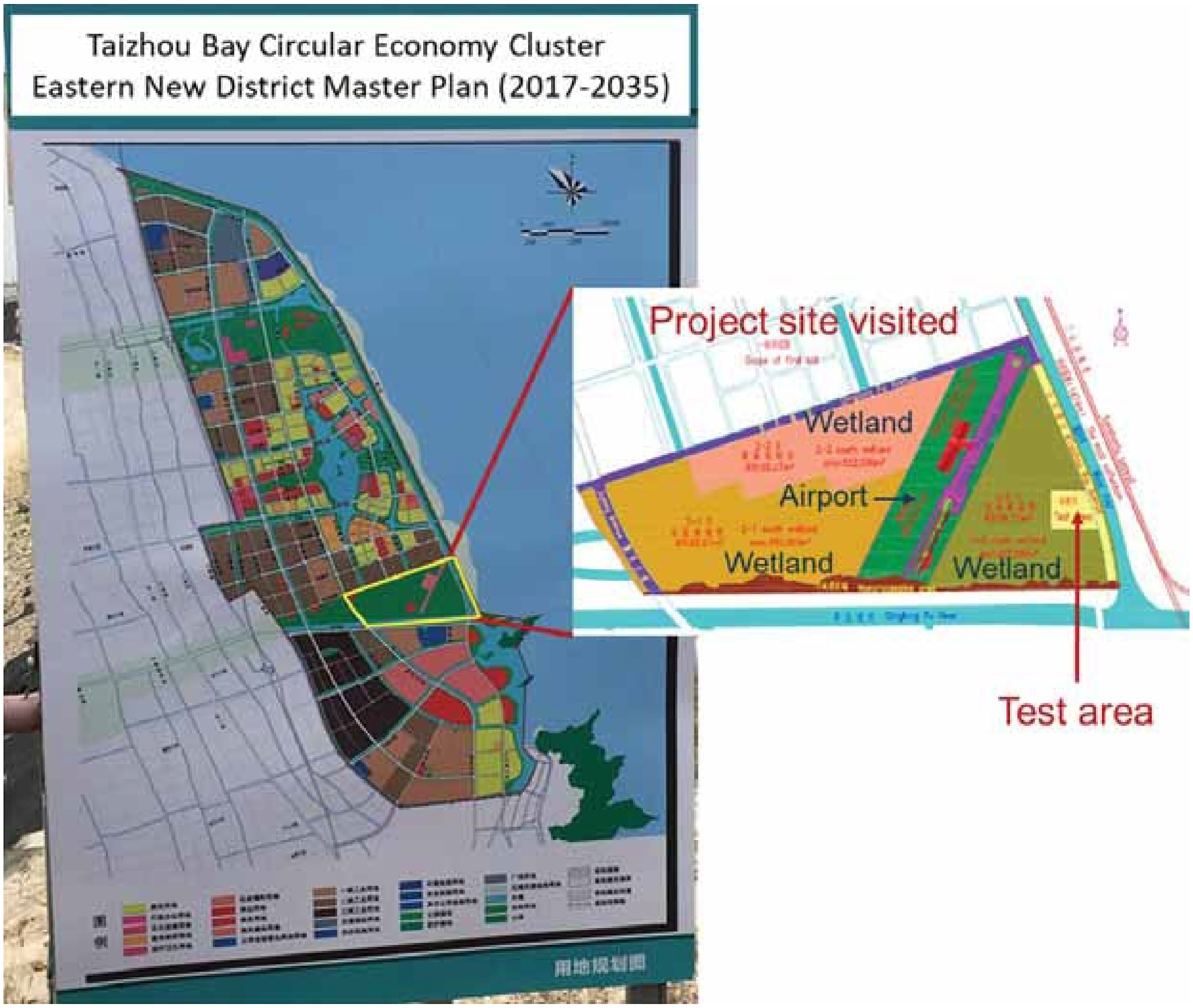


Fig. 8.5. Sketch of the dredged land in Taizhou treated by vacuum consolidation.

The ground surface was very soft and not stable for walking before a surface crust was formed from ditch drainage and natural drying. Vacuum preloading is used to consolidate the dredged fill to improve the strength and reduce post construction settlement. The objectives of the improvement were defined by two parameters, soil bearing capacity and long-term settlement. Different criteria were established for different areas based on the planned construction. A bearing capacity target of 40 to 80 kPa (5.8 to 11.6 psi) was set for roads and airport runways. The long-term settlement target was 300 mm (1 ft) over 15 to 30 years.

8.5 Traditional Vacuum Preloading and Improved Vacuum Preloading Process

Three versions of vacuum preloading were designed and field-tested at this project site: traditional vacuum preloading, improved vacuum preloading, and electro-osmosis assisted dewatering and consolidation. This section only reviews the traditional and improved vacuum preloading. The process of traditional vacuum preloading, as used at this site, included the following steps:

(1) Placing woven geotextile at the ground surface to assist site access;

(2) Installation of prefabricated vertical drains (PVDs);

(3) Laying horizontal vacuum tubes and connecting the vacuum tubes to PVDs;

(4) Laying sealing membrane and tugging and anchoring the membrane around the periphery ditches;

(5) Pumping and maintaining vacuum during the preloading process.

According to the engineers working on this project, the traditional vacuum preloading process suffers some shortcomings. The PVDs have relatively flexible cords which can be more easily bent before being inserted to the intended depths. The filter fabric around the PVDs can clog to form a filter cake. Bending and clogging of PVDs can have detrimental effects on the effectiveness of consolidation. The improved vacuum preloading at this site featured the following improvements:

1. A new PVD design with anti-caking drainage fabric of better apparent opening size (AOS) to match particle size of soil to be drained and stiffer core to prevent bending;

2. A more efficient connection between PVDs and horizontal vacuum tubes to allow each vacuum tube to connect two rows of PVDs (Fig. 8.6) using specially designed hand-shaped joint (Fig. 8.7);

3. A more powerfully (55 kW compared to 7.5 kW pump in the traditional vacuum preloading) and centrally located electric vacuum pump to withdraw air and water beneath the membrane to apply vacuum (Fig. 8.8). The new pump system was more efficient and saved electricity by 50% over the multiple smaller pumps what are traditionally used in the vacuum preloading method as shown in Fig. 8.9.

4. The vacuum tubes and PVDs can be used to inject high pressure air (air sparging) into the soil mass to prevent clogging and facilitate movements of water to speed up the consolidation.

Fig. 8.10 shows the area under vacuum preloading. Field tests were performed to compare the conventional vacuum preloading with the improved preloading. The tests showed the improved method was 20% more efficient than the traditional method in terms of the amount of consolidation settlement induced by vacuum pressure during the same time period.

Fig. 8.6 PVD Installation and connection to horizontal vacuum tubes

(a) Vacuum connection (b) Air injection point

Fig. 8.7. Hand-shaped PVD to vacuum connection and air injection point

(a) Centralized pump (b) Pipelines

Fig. 8.8. Centralized pump (55 kW) and pipeline connection to the pump house

Fig. 8.9. Multiple smaller water-jet vacuum pumps used on another project site (photo taken by Jie Han in 2010)

Fig. 8.10. Area under vacuum preloading

Water on top of the vacuum liner provides additional loading to consolidate soft clays, however, detecting and repairing the leaking liner below water can be challenging. The Chinese contractor cleverly used double layers of liner to solve the problem. The worker in Figure 8.11 is walking on the liner bare feet to feel any loose or bloated upper layer of the liner. When the liner leaks, the upper liner becomes loose and floated with air. The worker can drop a sand bag to seal the leakage location.

Fig. 8.11 Detect and repair leakage liner

Fig. 8.12 shows a row of 76 light weight wick drain installation rigs in a “small portion” of the newly reclaimed land. Each rig is skid mounted over a sliding frame to minimize the ground pressure. A light rail is used to transport equipment, drain materials, and workers.

Fig. 8.12. Light weight wick drain installation rigs over the very soft reclaimed land

8.6 Research Work and Key Findings

Extensive research has been devoted to enhance the efficiency of vacuum preloading, which has resulted in a variety of new developments. As described in Section 8.3, these new developments include the renovation of PVDs and their connection to horizontal vacuum tubes, the use of a more powerful and central pump, and the combined use of vacuum preloading with other processes (e.g. air sparging and lime modification). These innovations have been successfully applied to mass site improvement, such as land reclamation, leading to profound saving of construction cost and time.

8.7 Lessons Learned and Recommendations

Traditional vacuum preloading including pumping from prefabricated vertical drains (PVDs) connected with drainage pipes at the surface may suffer several shortcomings that render the method ineffective or less efficient. These shortcomings include clogging of the PVDs and formation of “cakes” or soil columns around the PVDs, bending of the PVDs to prevent their installation to a desired depth and difficulties in applying vacuum pressure to soils at great depth. To overcome these shortcomings, the researchers and engineers in China developed improved design of PVDs using more stiff cores and filter fabric tailored for the soil gradation of the site and innovative “hand-shaped” connections between the PVDs and horizontal drainage pipes. Furthermore, the researchers and engineers experimented with the vacuum preloading combined with other technologies, such as air sparging and chemical stabilization of the ground surface. They found the use of a large centralized electric pump system is more efficient and can save electricity over a net of small electric or diesel pumps.

In the United States as the readily developable lands are depleted, there are rising demands to develop sites that are underlain with weak and compressible soils. Ground improvement will be necessary to gain bearing capacities and limit post-construction settlements. Preloading using fill has been commonly used either with or without PVDs to control the rate of consolidation and preloading time. We believe vacuum preloading could be a viable and more cost-efficient alternative for some of the sites, especially for areas where fill material may not be readily available.

We recommend vacuum preloading be evaluated and experimented on one or more project sites. The experiment should be designed based on soil conditions, improvement objectives and other site constraints. The more ideal candidate sites would be large dredged material disposal sites or natural coastal lowlands for roadways or container port and large storage yard development. The experiment should be spearheaded by reputable geotechnical constructors aided by consulting geotechnical engineers and researchers. The experiment should develop design construction details to allow the use of vacuum preloading effectively and cost-efficiently on actual projects. Hopefully, the experience and confidence gained from these projects would allow more wide spread use of the technology where the site conditions are more conducive to the vacuum preloading ground improvement method.

9. ELECTRO-OSMOSIS ENHANCED PVD CONSOLIDATION

9.1 Introduction

Electrokinetic phenomena refer to a family of effects in heterogeneous fluids that are induced under electrical field. Electrokinetic phenomena were reported as early as 1809 (Reuss 1809). Over the years of applications and studies, it has been categorized into eight major phenomena: electrophoresis, electro-osmosis, diffusiophoresis, capillary osmosis, sedimentation potential, streaming potential/current, colloid vibration current, and electric sonic amplitude (Dukhin and Derjaguin 1974). In the past half century, electrokinetic phenomena have been utilized in soil dewatering, contamination remediation, fertilizer mobilization, land reclamation, waste water treatment, contaminant barrier, etc. (Lageman et al. 1989; Yao et al. 2012; Zhuang et al. 2015). Even though there have been plenty of promising data relevant to the application of electrokinetics all over the world, many fundamental mechanisms are still uncertain as they are rather complicated, involving electrical engineering, electro-chemistry, mineralogy, colloid-chemistry, material science, physics, and soil mechanics (Hunter 1989 and Zhuang et al. 2015).

Among the eight electrokinetic phenomena, electro-osmosis has been used for several decades as a soil improvement method, which refers to the directed flow of liquid in a porous medium upon the application of electric field. The flow is caused by the dragging effect of ions to the surrounding pore water. Since there are more cations than anions in the water, the flow driven by the electro-osmosis effect results in net water migration from anode to cathode as shown in Figure 9.1. Due to the movement of cations and anions, OH^- and H^+ are accumulated near anode and cathode, respectively, which lead to acid and base environments near the anode and the cathode accordingly.

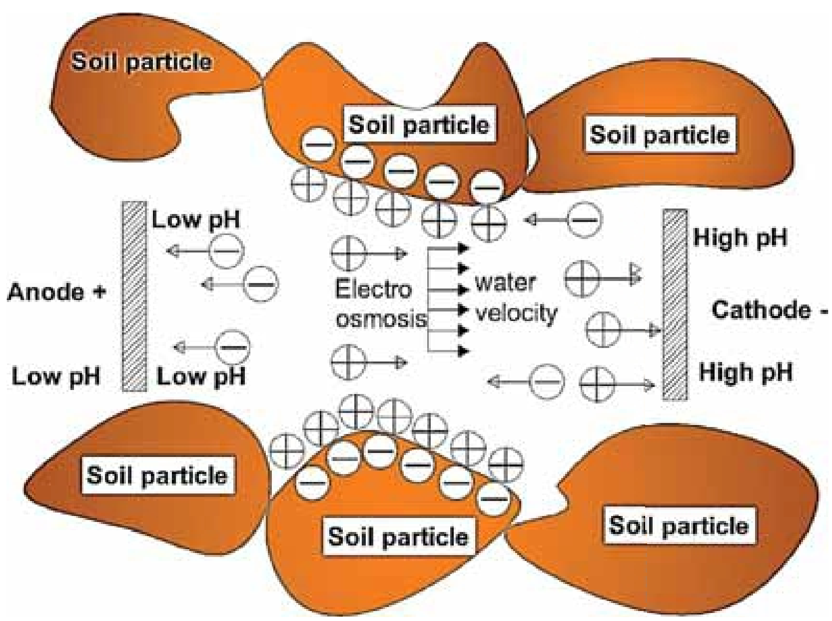


Fig. 9.1. Conceptual schematics of electro-osmosis (Moghadam et al. 2016)

The outstanding advantage of electro-osmosis is that it can significantly accelerate water flow in soil, especially soil with low permeability. Many studies have proved that, unlike hydraulic permeability, electro-osmotic permeability is essentially independent of grain size, which results in flow rates of 100 to 10,000 times greater than hydraulic flow in fine-grained soils (Jones et al. 2008). Table 9.1 summarizes the electrical permeability of commonly encountered soils.

Table 9.1 Electrical permeability of different soil (Zhuang et al. 2015)

Type of soil	Water content (%)	Electric permeability (x 10^{-9}/s v)	Type of soil	Water content (%)	Electric permeability (x 10^{-9}/s v)
London clay	52.3	5.8	Boston clay	50.8	5.1
Kaolinite	67.7	5.7	England loam	31.7	5.0
New York dust	27.2	4.5	England marl	29.1	2.6
Calcium bentonite	170.0	2.0	Mica powder	49.7	6.9
Fine sand	26.0	4.1	Quartz powder	23.5	4.3

9.2 Description of technology

The application of electro-osmosis for dewatering or consolidation involves installing anodes and cathodes into soil and removing water from the cathodes. Depending on the targeted flow direction, the electrode array can be arranged in different patterns to achieve different flow patterns, for example, parallel flow and radial flow. In recent years, electro-osmosis dewatering/consolidation has been used in conjunction with preloading/vacuum preloading to further expedite the water flow and reduce the soil void ratio (Wang et al. 2014; Sun et al. 2017).

Even though electro-osmosis has been used in practice for several decades, its application has not been as popular as many other dewatering/consolidation techniques, for example, PVDs and preloading, for two major reasons: (1) the energy consumption is high, which leads to high total cost and (2) the corrosion of electrodes is a challenging issue in the field (Zhuang et al. 2014 and Zhuang 2015). Newly emerging Electrokinetic Geosynthetics (EKG) plausibly solve the problem of electrode corrosion, which makes the application possible in various harsh environments (Hamir et al. 2001; Jones et al. 2011). In general, electro-osmosis is now more commonly used in the projects where other techniques are ineffective, or timing is crucial.

The concept of EKG was first presented more than 20 years ago (Jones 1996; Nettleton et al. 1998). In its early age, EKG was manufactured by embedding metal wires or rods into geosynthetics to form sheets or tubes. In recent years, China has patented an EKG, which was made from conductive polymer with resistivity of 10^{-3} Ω·m as shown in Figure 9.2. The EKG was flexible and made into a PVD-like shape to allow it to be installed by the existing PVD installer. Two copper wires of 1 mm in diameter were included to assist the current distribution as well as provide convenience for the connection with electrical source. Even though such an EKG does not bring the total cost down, it makes fast installation possible in the field, which is important for large-scale projects.

Fig. 9.2. EKG made from conductive polymer (patented in China in 2012).

9.3 Theories of electro-osmosis dewatering/consolidation

Based on the Terzaghi consolidation framework, Esrig (1968) suggested the electro-osmosis water flow in the soil skeleton is counteracted by the flow driven by the hydraulic gradient in the opposite direction. In other words, the flow ceases when the electro-osmosis and hydraulic gradients balance each other. Based on his theory, Terzaghi's consolidation formula is still valid, i.e.,

$$C_v = \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \qquad (9\text{-}1)$$

where C_v is the coefficient of consolidation, u is the pore water pressure, t is time, and z is the drainage distance.

Based on Esrig's theory, the following boundary condition should apply to consider electro-osmosis flow during consolidation:

$$
\begin{cases} t = 0,\ 0 < z < H; u(z)|_{t=0} = u_o(\beta - \frac{\alpha z}{H}) \\ 0 < t < \infty, z = 0; u|_{z=0} = 0 \\ 0 < t < \infty, z = H; \frac{\partial u}{\partial z}|_{z=H} = \frac{k_e}{k_h}\gamma_w \frac{v_o}{H} \end{cases} \quad (9\text{-}2)
$$

where u_o, α, and β are constants to describe the initial spatial distribution of pore water pressure, H is the distance between anode and cathode, k_e and k_h are electrical and hydraulic permeability, respectively, γ_w is the unit weight of water, and v_o is the voltage between anode and cathode.

The Helmholtz-Smoluhowski theory (Helmholtz 1879; Smuluchowski 1914; Mitchell 1991; Mitchell and Soga 2005) is used to estimate the electrical permeability, k_e, which treats the double layer as a capacitor.

$$
k_e = \frac{\zeta \varepsilon n}{4\pi\eta} \quad (9\text{-}3)
$$

where ζ is the potential of the double layer, ε is the dielectric coefficient, n is the soil porosity, and η is the viscosity of water.

Equations 9-2 and 9-3 can be used to calculate the total water removed from soil, by assuming that the soil remains saturated during dewatering/consolidation. However, the soil will have a high chance of becoming unsaturated due to the high water flow rate. In addition, the unstated assumption for the equations is that the current is constant, which may not be true for many occasions. To improve the accuracy and broaden the application into unsaturated soil, Zhuang et al. (2005) and Zhuang and Wang (2005) proposed a so-called "energy level gradient theory", which was based on the accumulation, consumption, and transformation of energy. Based on this theory, the total volume (Q) of electro-osmotic dewatering can be estimated by:

$$
Q = k_q \frac{V(I_{ototal} - I_{\infty total})}{a^2 \Delta x^2}(1 - e^{-at}) \quad (9\text{-}4)
$$

where k_q is the flow rate coefficient ($m^2 \cdot Pa^{-1} \cdot s^{-1}$), V is the voltage applied on the soil (V), I_o is the initiate electric current (A), I is levelled off electric current (A), t is time (s), a is the time factor (s^{-1}), Δx is the distance between anode and cathode (m), and

$$
I_{ototal} = N j_o A \quad (9\text{-}5)
$$

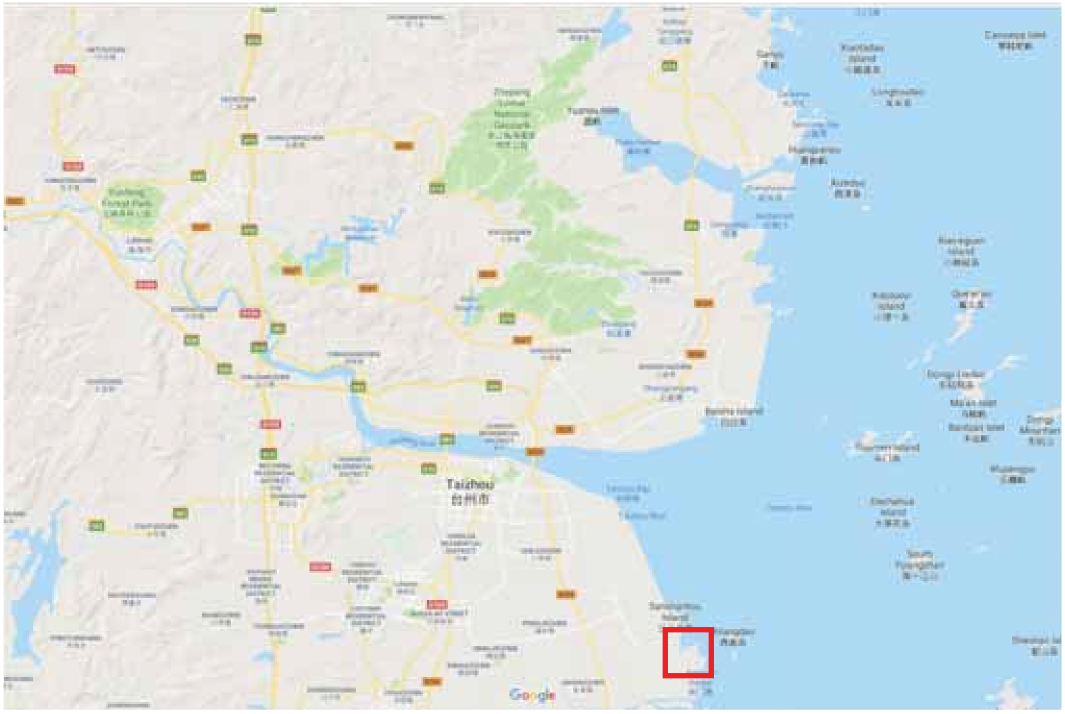
$$I_{total} = (I_{ototal} - I_{\infty total})e^{-at} + I_{\infty total} \qquad (9\text{-}6)$$

where I_{total}, I_{0total}, and $I_{t\ \ otal}$ are total electric currents of t moment, initial time, and infinity (A), respectively, j_0 is the initial surface current density ($A \cdot m^{-2}$), N is the number of circuits (dimensionless), and A is the area perpendicular to the electric current (m^2).

9.4 Project site information

The project involves dredging marine deposits to reclaim 2.528 million square meters of land for residential and commercial usage. The project is located in the City of Taizhou, Zhejiang Province of China, which is 400 km (240 miles) south of Shanghai as shown in Figure 9.3. The project is on the west shoreline of the East China Sea and at the Taizhou Bay where the Jiaojiang River enters the East China Sea as shown Figure 9.4.

Fig. 9.3. Geographic location of Taizhou, Zhejiang, China



(a) Taizhou Bay

(b) Site location

Fig. 9.4. Location of the project site (source: Huadong Engineering Co. Ltd.)

After dredging was completed, a site investigation indicated that below the 5 - 6 m (16 – 20 ft) dredging fill there was 22 - 26 m (72 – 85 ft) of peat and more than 20 m (66 ft) of silty clay layer as shown in the boring log in Figure 9.5. The soil testing showed that the dredging fill had a moisture content of 50 ~ 83% and could only provide a bearing capacity of 20 - 30 kPa (418 – 627 psf), which prohibited any construction activities. In addition, the underlying peat and silt clay had moisture contents of 46 ~75% and 33 ~ 59%, respectively. The reclaimed area will be used for manufacturing plants, roads, park areas, and an airport. Therefore, the top 1.5 m (5 ft) needed to be first treated to reduce its compressibility and increase its bearing capacity to give access to construction equipment and personnel. For most of the reclaimed area, the PVD and vacuum preloading were used together to remove the water from the soil. On the east side of the reclaimed area, a 1,000 m^2 (10,800 ft^2) area was selected as a test area (shown in Figure 9.6 as “Test area”) where electro-osmosis and vacuum preloading were used jointly, hoping to achieve fast dewatering/consolidation than other methods. The 1,000 m^2 (10,800 ft^2) was divided equally into 5 sections (K1, K2, K3, K4 and K5), i.e., 200 m^2 (2,150 ft^2) per section. The designed treatment depths for the 5 sections were 0, 5, 7, 9 and 10 m (0, 16, 23, 30, and 33 ft), respectively. The zero depth represented the vacuum preloading only situation.

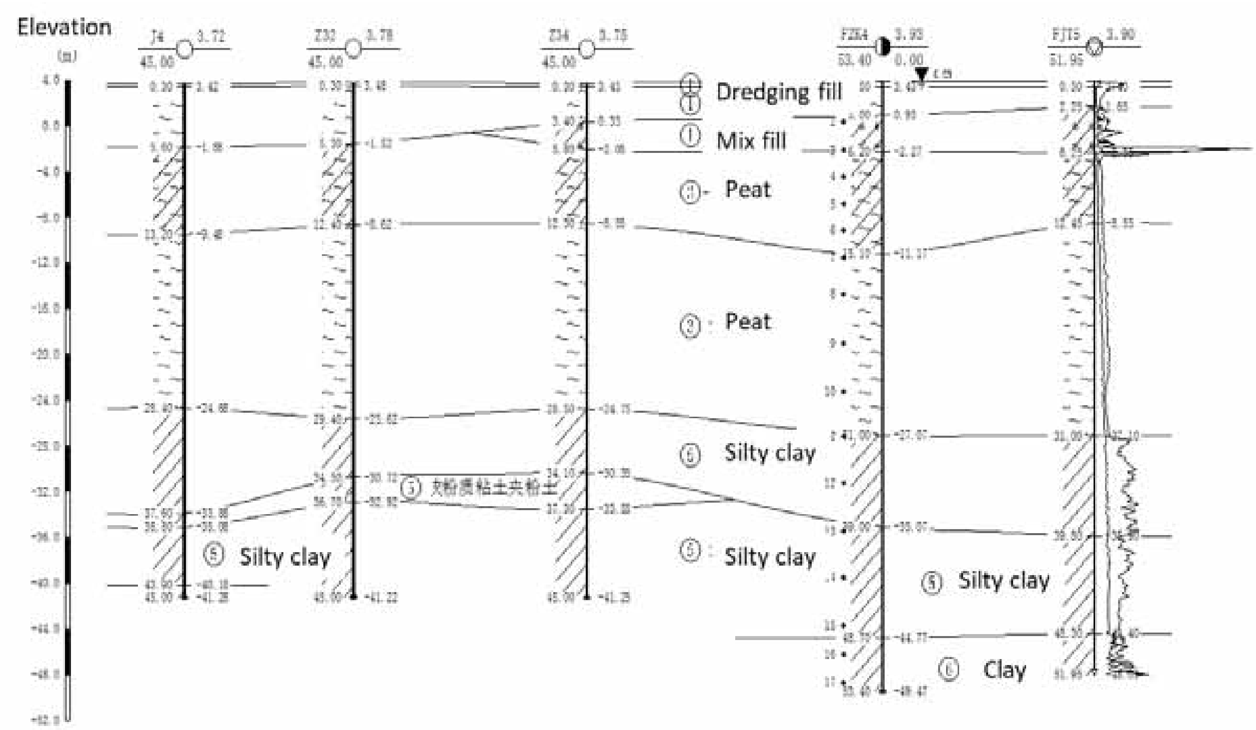


Fig. 9.5. Boring log of the project site (source: Huadong Engineering Co. Ltd.).

Fig. 9.6. Electro-osmosis + vacuum preloading test area
(source: Huadong Engineering Co. Ltd.)

9.4 Electro-osmosis design and PVD installation

The PVD used for electro-osmosis consisted of an EKG core (shown in Figure 9.2) and a geotextile sleeve, which looked like a conventional PVD. The properties of the used EKG PVD are listed in Table 9.2.

Table 9.2. Properties of PVD with EKG core

Specimen	Resistance (Ω·m)	Elongation (%)	Tensile strength (MPa)
EKG PVD	4.0486×10^{-3}	9.32	4.46

Before installation, design was performed to determine the key parameters of the electro-osmosis dewatering/consolidation following the procedure below (Zhuang 2016):

- Obtain flow rate coefficient, k_q, time factor and initial surface current density j_0 through lab scale model tests,
- Select DC power, electrode spacing, and rolling electro-osmosis scheme according to dewatering time requirement and project budget and calculate initial total current,

- Calculate dewatering time according to current - time curve,
- Calculate total dewatering volume; estimate water content of sludge after electro-osmotic dewatering; and estimate the settlement after consolidation. If final moisture content and settlement do not meet the criteria, go to Step 2 to re-select DC power and rolling electro-osmosis scheme and repeat the remaining steps.

Based on the design, the layout of each test section is presented in Figure 9.7. The PVDs were installed with 1 m spacing in both horizontal and vertical directions. For each section, two DC power sources of 80V/100A were used as shown in Figures 9.7 and 9.8. The DC power sources were computer-controlled and uplinked to internet for remote control and record of the electro-osmosis process. Five alternating rows of PVDs were connected to the anode of the power source and the other five alternating rows of PVDs were connect to the cathode of the same power source, which was expected to form parallel flow in the soil mass. At the boundary of each test section, 0.5 m space was reserved to allow the anchorage of geomembrane used for the vacuum preloading. The site control computer turned on and off the DC power supply for each group of PVDs with a pre-planned duration and electric current alternatively.

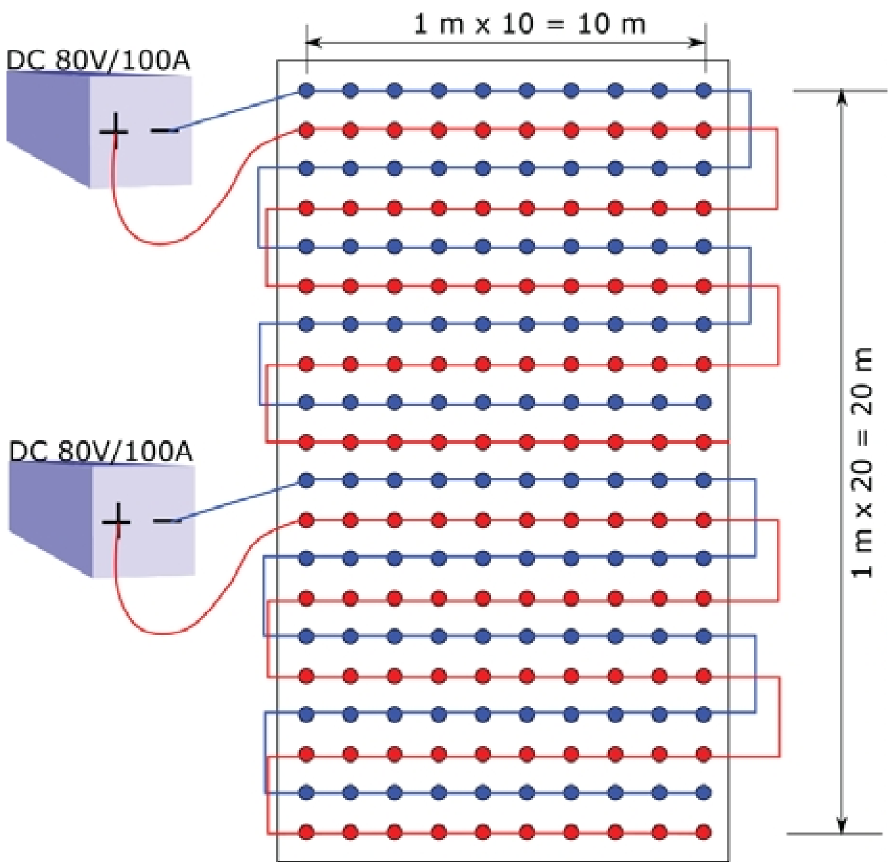


Fig. 9.7. Layout and connection theme of PVDs
(source: Hangzhou Shenyuan Environmental Sci-Tech Co. Ltd.)

Fig. 9.8. DC power source and control panel

The installation includes the following procedure also shown in Figure 9.9:

- Lay out a layer of geotextile to allow access of equipment and personnel.
- Install PVDs (note: 4 different depths were used for different sections).
- Lay out and connect surface drainage pipes, which were used to guide water to ditches at sides of each section.
- Wrap PVDs around pipes and then connect them to wires that were then connected to a connector. The connection theme of PVDs is shown in Figure 9.7. The pipes were used to guide water out at the cathodes.
- Lay out a layer of geotextile and a layer of geomembrane sequentially.
- Connect the pipe to a vacuum pump and then connect wire to the power source. The vacuum preloading started first and the power for the electro-osmosis dewatering/consolidation was not started until 7 days after the start of vacuum preloading.

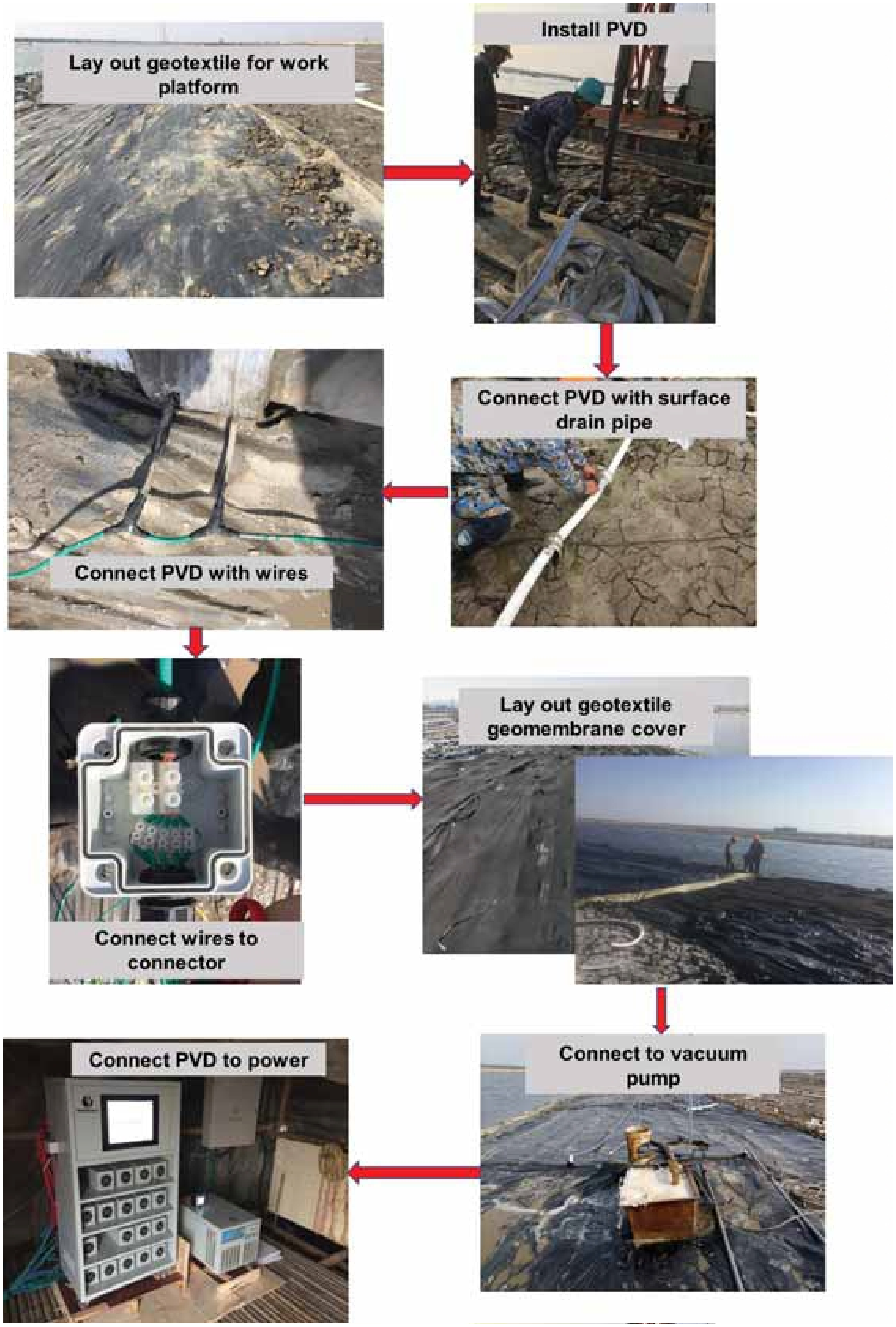


Fig. 9.9. Procedure of installation and construction
(source: Hangzhou Shenyuan Environmental Sci-Tech Co. Ltd.)

9.5 Key findings and future study

The visited site was a test area to assess the effectiveness of a combined use of electro-osmosis and vacuum preloading techniques. In the test zone, instrumentation monitored the site lateral and vertical movements and the ground water table depth, as shown in Figure 9.10. Even though the test site is rather small compared with the whole project site (i.e., 1,000 vs. 2.5×10^6 m^2 or 1.1×10^4 vs. 2.7×10^7 ft^2), the achieved results are very encouraging. The remaining of the project site was primarily treated with vacuum preloading with conventional PVDs. The treatment was still in progress at time the project site was visited on May 25, 2018. Based on the data obtained, the measured settlement ranged from 500 to 750 mm (20 to 30 in) for the five areas at 32 days since the start of electro-osmosis dewatering/consolidation.

The values were significantly higher than these obtained from the neighboring areas, indicating that the testing was successful in terms of the achieved outcome. The technology showed its advantage in fine-grain soil, especially under unsaturated situations, compared to other methods. The visit leads many other important findings:

- The technology is labor intensive because it involves connecting PVDs with wire and water proof connectors have to be used to preserve the voltage.
- The cost of this technology is high as compared with vacuum preloading only, which comes from energy consumption and EKG PVDs. The energy consumption ranged from 4 to 7 kwh/m^3 (0.11 to 0.20 kwh/ft^3). It is possible to supplement the energy from solar source to offset the total cost in the day time. The EKG PVD is expensive compared with conventional ones because the demand in the market is still small. However, with an increased application of such a method, the cost of EKG PVD can be reduced if the increase of demand leads to massive production. The outstanding advantage of such a method is that it is several times faster than conventional PVDs. Based on a rough estimate from the visited project, it is approximately 4 or 5 times faster. The reduction of construction time may be able to offset higher cost for some applications.
- The system used in the visited project was testing a function of switching power anode and cathode to further improve the efficiency of this technology. This function seemed interesting and encouraging.
- The conductivity of EKG PVD will decrease gradually due to the leaching of the conductive chemical compounds. In addition, due to the accumulation of chemicals around the electrodes, the current may be significantly reduced during operation. These issues may become a problem for a dewatering project lasting for years. However, as to a project only lasting for a few months, they may not be a problem. The system used in the visited project had lasted for months without any significant leaching observed.

- Alternative power supply can be used to save power consumption. For example, solar panels may be used to supply power for this system.

In summary, electro-osmosis dewatering/consolidation is a promising soil improvement technology to treat dredging fill in a large-scale.

Fig. 9.10. Site instrumentation monitoring lateral and vertical movements, and water table depth.

10. BIO-STABILIZATION

10.1 Introduction

During the last decades, biological processes and products have been investigated for their use in ground improvement applications, due to their potential to improve sustainability and reduce environmental impacts of geotechnical engineering practice. There are many naturally occurring subsurface biological processes that alter the hydrological and mechanical properties of soils. Biophysical processes such as burrowing animals or plant roots change soil properties as they may desaturate, compact, loosen or segregate sediments. Biochemical processes may dissolve, oxidize, hydrolyze or precipitate minerals, as well as produce or degrade organic biomass or produce gas. These biochemical conversions may change porosity, saturation, create cementing bonds, change the pore structure, or composition of soils. Consequently, these processes may significantly affect hydrological and mechanical properties. For example the lump of silty soil used for land reclamation in Taizhou shown in Figure 10.1 shows signs of biological activity, which affects the soil properties, such as the discoloration from grey to brown indicates that part of the soil is being oxidized and tiny wormholes.

Fig. 10.1 Discoloration through oxidation and tiny wormholes in the silty soils used or the land reclamation in Taizhou affecting the soil behavior

Mixing biological materials with sediments may also improve soil behavior. Materials, such as organic fibers, polymers, organic acids, or products of (partial) combustion of biological materials (e.g. charcoal, siliceous ash or calcareous lime) may affect the consistency, compression, and swelling behavior of fine grained soils or act as stabilizing agents in granular soils. During the 2nd China-US workshop on Ground Improvement Technologies organized on May 28, 2018 in Shanghai, two presentations were provided by Leon van Paassen and Jia He. The current state of the art of bio-based ground improvement was presented, focusing on two processes: 1) microbially induced carbonate precipitation by urea hydrolysis and 2) microbially induced desaturation and precipitation through denitrification. This section of the report provides an overview of the recent developments on bio-stabilization based on the presentations provided during the workshop, as well as discussions and exchanges that followed.

10.2 Description of the technology

Various biochemical processes exist, which may be used for ground improvement applications (Khodadadi et al. 2017). The main process under investigation is microbial-induced calcium carbonate precipitation (MICP) through urea hydrolysis (e.g. DeJong et al. 2006; Whiffin et al. 2007; De Jong et al. 2010). This process involves urease-containing micro-organisms. The urease enzyme catalyzes the hydrolysis of urea and is found in a wide range of bacterial species and plants. Urea hydrolyzing bacteria can be cultivated and injected in the ground (bio-augmentation) or they can be stimulated to grow in the ground (bio-stimulation). Supplying these micro-organisms with a solution of urea and calcium chloride will result in the hydrolysis of urea and consequent precipitation of calcium carbonate:

$$CO(NH_2)_2 + Ca^{2+} + 2H_2O \rightarrow 2NH_4^+ + CaCO_3 \qquad (10\text{-}1)$$

The calcium carbonate minerals formed by MICP reduce soil porosity and permeability and may increase soil strength and stiffness. The remaining ammonium chloride needs to be extracted and disposed. Substrates and bacteria can be supplied into the subsurface by injection and extraction, by surface percolation or through in situ mixing. The low viscosity of the substrate solutions, controllable reaction time, and remaining permeability after treatment allow for multiple injections over large distances under low pressure gradients. These process characteristics are unique in comparison with alternative ground improvement techniques, such as cement- or chemical-based deep mixing, jet grouting or permeation grouting methods. The two main biological processes leading to precipitation of calcium carbonate are urea hydrolysis and denitrification as shown in Figure 10.2.

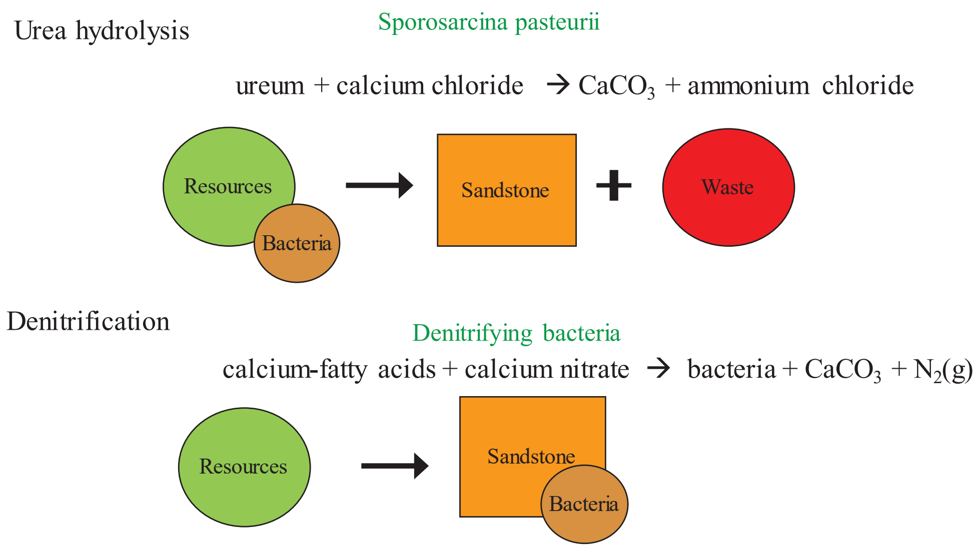


Fig. 10.2. Two main biological processes leading to precipitation of calcium carbonate.

Alternative processes resulting in precipitation of calcium carbonate have been explored, particularly MICP by denitrification. In this process, a solution containing nitrate, calcium, and acetate (or another soluble source of organic carbon with some additional nutrients and trace elements to stimulate microbial growth) is injected in the ground. The acetate is oxidized by indigenous denitrifying bacteria, which use nitrate as oxidizing agent.

$$5Ca(C_2H_3O_2)_2 + 8Ca(NO_3)_2 \rightarrow 13CaCO_3 + 8N_2 + 7CO_2 + 15H_2O \qquad (10\text{-}2)$$

Reduction of nitrate to nitrogen gas involves multiple steps:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad (10\text{-}3)$$

The intermediate products nitrite (NO_2^-), nitric oxide (NO), and nitrous oxide (N_2O) are toxic for the bacteria. Additionally, N_2O is a very strong greenhouse gas. Accumulation and emission of these intermediate products can be avoided by applying an appropriate substrate ratio and concentrations. Similar to MICP by urea hydrolysis, the precipitation of calcium carbonate reduces soil porosity and permeability, and increases soil density, strength and stiffness. The other product of the reaction is nitrogen (and carbon dioxide) gas. The gas fills up the pores space and reduces permeability and it also increases the compressibility of the pore fluid and dampens pore pressure build up during undrained loading, which may be used to mitigate earthquake-induced liquefaction (Rebata-Landa and Santamarina, 2012; He et al. 2013; He and Chu 2014). Besides gas and minerals, the denitrification reaction provides energy, in which the denitrifying bacteria can be used to convert part of the substrates into biomass. Biomass may also fill up the pores and reduce permeability.

10.3 Project site

The potential of MICP through urea hydrolysis for ground improvement applications has been demonstrated laboratory and large scale experiments as shown in Figure 10.3 (Van Paassen et al., 2009a, 2010a,b; Van Paassen 2011; Esnault Filet et al. 2012; Nassar et al. 2018) as shown in Figure 10.3 and a wide range of applications is foreseen (Phillips et al. 2013).

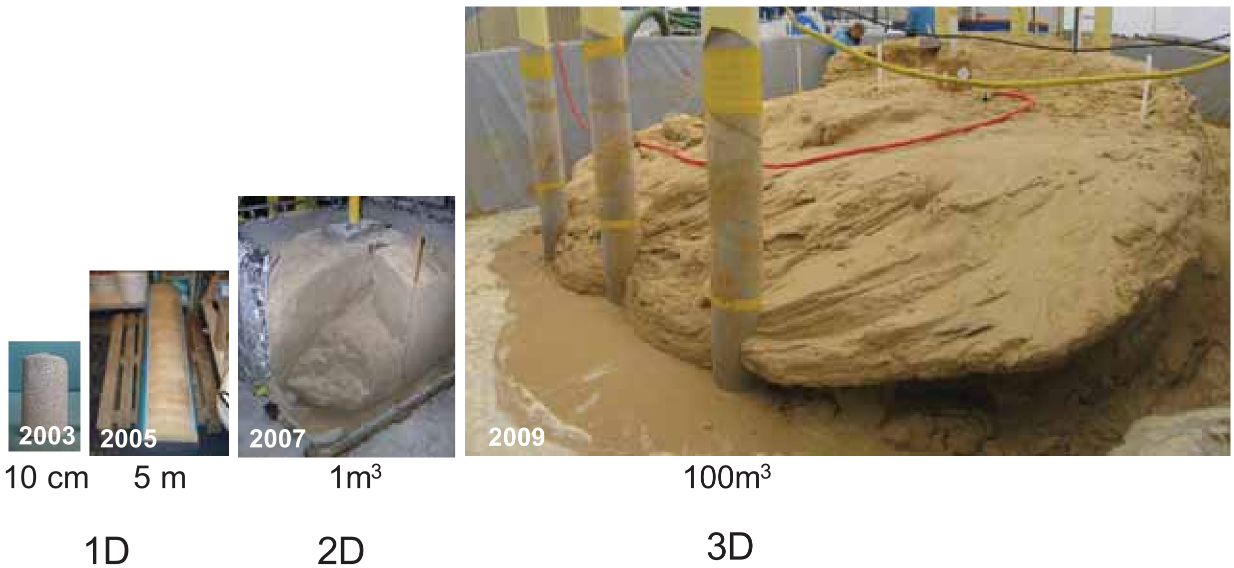


Fig. 10.3. Scale-up of Microbially Induced Carbonate Precipitation (MICP) by urea hydrolysis (Van Paassen et al 2009)

Several field trials have been performed for applications, such as immobilizing radionuclide and heavy metal contaminants in groundwater through co-precipitation with calcite in a sandy aquifer (e.g., Fujita et al. 2008; Li et al. 2013), stabilizing a sandy gravel to prevent borehole collapse during directional drilling underneath a river (Van der Star et al. 2011; Van Paassen 2011; DeJong et al. 2013), reducing the permeability to control contaminant transport in fractured rocks (Cuthbert et al. 2013), improving erosion resistance to control dust formation (Gomez et al. 2015), or prevent beach erosion (Danjo and Kawasaki 2016), and fracture sealing within a cement liner in a wellbore environment to enable CO_2 sequestration in old reservoirs (Phillips et al. 2013).

Although the technical feasibility to use MICP by urea hydrolysis as a bio-based ground improvement method has been demonstrated at large scale and several field trials have been performed, commercialization of the technology is still limited. For widespread use and adoption, MICP by urea hydrolysis process optimization for cost and environmental impact reduction and treatment effectiveness is needed.

One of the reasons for the limited applicability is the costs to implement the process at a larger scale. The initial cost estimates indicated that MICP by urea hydrolysis would be significantly more cost effective than alternative chemical grouting techniques (Ivanov and Chu, 2008). However, based on the first field trials the expected costs are estimated to range from 150 to 400 USD /m^3 (4.2 to 11.3 USD/ft^3) of treated soil, depending on how the volume is determined. These costs seem to be in the same range as jet grouting or chemical grouting, but significantly more expensive than mechanical or hydraulic ground improvement methods, such as dynamic compaction or consolidation and drainage. Costs for bio-stabilization by urea hydrolysis were approximately equally divided over the required substrates urea and calcium chloride, the cultivation of bacteria, the extraction and disposal of the residual ammonium chloride and mobilization of equipment.

Besides the monetary costs, the environmental impact of the urea-based process is not negligible because urea is a commercial fertilizer made from fossil fuels and the remaining byproduct ammonium chloride may lead to eutrophication of ground and surface water. Preliminary Life Cycle Analysis (LCA) has shown that MICP by urea hydrolysis can have a higher environmental impact than traditional ground improvement techniques using cement, such as jet grouting (Salemans and Blauw 2010). However, a direct comparison between these techniques is difficult, as the impacts may vary for different applications or cannot easily be quantified and the properties of the resulting cemented sand are not the same.

MICP via denitrification has not yet been demonstrated at large scale. However, it may prove to have potential for ground improvement applications, due to the lack of byproducts, the ability to use indigenous bacteria and the potential to use industrial waste streams rich in organic matter and nitrate as substrates (Van Paassen 2009; Van der Star et al. 2009, 2011; Van Paassen et al. 2010b; Pham et al. 2016; O'Donnell et al. 2017b). However, the process is significantly slower and requires lower concentrations to be used in order to avoid accumulation of intermediate nitrogen compounds. Hence, MICP via denitrification requires more flushes and longer treatment time compared to the urea hydrolysis to achieve sufficient calcite precipitation.

Employing denitrification to induce partial saturation through nitrogen gas production may prove more feasible (Rebata-Landa & Santamarina, 2012; He et al., 2013; He & Chu, 2014), The amount of substrates required to lower the degree of saturation of a sandy soil, is very small compared to the required substrates for cementation. Kavazanjian et al. (2015) renamed the process to Microbially Induced Desaturation and Precipitation (MIDP) and suggested to use it as a two-stage process to mitigate earthquake-induced liquefaction (Kavazanjian et al., 2015; O'Donnell et al., 2017a,b; Pham et al, 2018): Within several days, soil can be desaturated with a single flush with low substrate concentration. By supplying larger amounts of substrates in multiple flushes over a long treatment time (weeks to months), the soil can be cemented. No field trials have been performed demonstrating the potential of using biogenic gas formation to mitigate earthquake-induced liquefaction. However, other methods to induce partial saturation, e.g. by direct gas sparging (Okamura et al. 2010), drainage and recharge, injection of chemically reactive solutes (Yegian et al. 2007, 2013; Esseler-Bayat et al. 2012) or placement of stone columns (Okamura et al. 2006), have been suggested or demonstrated in the field. Okamura et al. (2006) showed that once the gas is introduced, the soil remains partially saturated for several years.

Finally, quality assessment and control at field scale are important aspects for practical applications. Most upscaling experiments performed so far show significant heterogeneity in the distribution of calcium carbonate and related geotechnical characteristics at small scale and over larger distances (e.g. Whiffin et al 2007; Van Paassen et al. 2010a; Martinez et al. 2011). The heterogeneity upon treatment is further exacerbated by the initial heterogeneities in the structure, texture and stratigraphy of soil be treated. Empirical correlations have been developed to enable design treatment and monitoring procedures and monitoring for field deployment evaluation. Still, insufficient experience and lack of guidelines make it difficult for potential project owners, consultants, and contractors to adopt these new technologies. This may also be the case in China, where the project manager needs to take more responsibility, when using a new technology. Practitioners still need guidelines for design and construction and appropriate and validated methods for QA/QC.

Despite the currently understood limitations of these bio-stabilization methods, there still may be applications in which widely adopted solutions are not possible, desired, or cost-effective. Mitigating beach erosion, liquefaction underneath existing structures, or dust control may lead to early adoption for bio-based ground improvement methods because treatment heterogeneity may be less important, the required strength may be small, or the site may be poorly accessible. Contractors and consultants in China advised different strategies for adoption, including the combination of bio-stabilization with other mature techniques or implementation of these technologies at pilot-scale within existing larger projects to prove engineering quality and allow contractors to gain experience. More field data could help improve both monitoring and quality control, while giving impetus to the development of the bio-stabilization method in return. Understanding when and where to apply for these new ground improvement methods are great factors when deciding technology applicability for contractors or managers.

10.4 Research work and key findings

Current research objectives include: 1) evaluating the performance of bio-stabilization methods for various soil types, environmental conditions or applications, 2) developing theoretical models for prediction and control, 3) developing and evaluating monitoring methods to assess the process performance, and 4) optimizing the process and reduce costs for practical implementation.

Considering the technologies are still in development, many researchers still focus on bench-top laboratory studies to investigate factors affecting the process performance, such as soil type, soil properties, and environmental conditions (e.g. Mortensen et al. 2011; El Mountassir et al. 2018; Zamani & Montoya 2019). Most researchers in China studied the process performance of bio-cemented sand using MICP by urea hydrolysis. For example, Cheng et al. (2013) performed cyclic triaxial tests and shake table tests on bio-cemented sands to identify the potential of bio-based methods to improve the soil performance under dynamic loading. Liu et al. (2018) also focused on the cyclic response using bio-cemented calcareous sands. Peng et al. (2016) reported that lower temperatures reduced the reaction rate, process efficiency, and lowered the resulting unconfined compressive strength. Cui et al. (2015) varied the concentrations of urea and calcium chloride to find an optimum conversion efficiency and assessed the process performance based on calcium carbonate content and unconfined compressive strength. While, Sun et al. (2017) showed that using calcium acetate as calcium source resulted in a higher conversion efficiency by varying the type and concentration of substrate.

Cheng and Cord-Ruwisch (2013) developed a method to enrich ureolytic bacteria from soils under non-sterile conditions, which could significantly reduce the cost for bacterial cultivation. Burbank et al. (2011) and Gomez et al. (2014) developed methods to stimulate growth of indigenous ureolytic bacteria *in situ*. Whereas, others try to find and optimize extraction of urease enzymes from lysed bacterial cells or from alternative plant-based sources of urease (Terzis and Laloui 2018; He et al. 2018; Hamdan et al. 2016).

Several researchers aim to reduce the required amount of substrates by improving the efficiency of substrate conversion (Al Qabany et al. 2011; Terzis et al. 2016) or obtain a high strength at a lower cement content by improving the cementation efficiency or using additives such as casein or fibers. Others are aiming to find solutions to deal with the residual ammonium chloride (Gomez et al. 2014, 2017).

To improve process prediction and control, theoretical models are being developed, with various levels of complexity (Van Wijngaarden et al. 2011; 2013, 2016a,b; Ebigbo et al. 2012; Nassar et al. 2018; Hommel et al. 2013, 2015, 2016) which allow to predict the spatial and time-dependent distributions of the reaction products. Empirical correlations have been established, relating the amount of calcium carbonate to geotechnical properties, such as strength, stiffness, porosity and permeability. These theoretical models and empirical correlations can be used to design treatment procedures, in which process outcomes (distribution of calcium carbonate, changes in soil properties such as strength or stiffness, costs and/or environmental impacts) can be predicted as a function of the process variables (bacterial activity, substrate concentration, amount of injections, injection strategy, pumping rate, and/or time) and initial ground conditions (soil type, grain size distribution, grain texture, packing density, initial porosity, permeability, etc.).

The potential of MICP through denitrification has been demonstrated in the laboratory (Van Paassen et al. 2010b; O'Donnell et al. 2017b; Pham et al. 2016). When employing the denitrification process to induce calcium carbonate precipitation for soil cementation a larger amount of substrates is required. As a result, several pore volumes of gas will be produced. Rebata Landa and Santamarina (2012) and He and Chu (2014) showed that desaturation through by biogenic nitrogen gas formation can significantly reduce the pore pressure response during cyclic loading. A basic theoretical framework is developed to predict the volume of gas produced and the related degree of saturation to the pressure conditions and amount of consumed substrate, which was experimentally validated (Van Paassen et al. 2017, Pham et al. 2016, 2018). However, measures should be taken to avoid gas entrapment as sudden release of the gas may cause instability (Grozic et al. 1998) instead of mitigating it. The metabolic conversion of substrates will also lead to the formation of biomass.

Compared to urea hydrolysis, lower concentrations must be used to avoid accumulation of intermediate nitrogen compounds and thus multiple flushes are required to obtain a significant amount of cementation. Pham et al. (2018) evaluated different injection strategies. Choosing between a low number of flushes with higher concentration and a high number of flushes with low concentration they proved the low concentration treatment showed higher efficiency. They also showed that formation of the gas and biofilm affect the hydraulic conductivity. Further investigations are required to scale up this process and improve understanding about the coupled interaction between these processes and products.

10.5 Identified innovations

Although MICP via urea hydrolysis and denitrification have been investigated and associated with carbonate precipitation for more than a century (e.g. Beijerinck 1901; Bavendamm 1932), investigations to their potential use in geotechnical engineering applications started in the late 1990's. There are still limited field-scale projects, which rely on the bio-stabilization processes, especially in China. Still, significant application-specific innovations have been made, for which numerous patents have been filed, including

(1) the use of MICP by urea hydrolysis to lower the permeability for selective plugging of oil reservoirs (Ferris and Stehmeier 1992),
(2) the use of MICP by urea hydrolysis as method to cement soils (Hamelin et al. 2008; Darson-Balleur and Girinsky 2012; Kucharski et al. 2012; Esnault et al. 2016),
(3) a procedure to fix and improve the distribution of ureolytic bacteria (Van Paassen et al. 2009),
(4) a procedure to stimulate indigenous bacteria to form calcium carbonate (Crawford et al. 2013),
(5) the use of isolated enzymes to precipitate minerals in porous media (Hamdan & Kavazanjian 2016), or
(6) a gas delivery system to provide induced partial saturation through solute transport and reactivity for liquefaction mitigation (Yegian and Alshawabkeh 2013).

In China, a large amount of patents and student dissertations can be found going far beyond the published research papers. Application status of a new technology in China is available through WanFang (http://g.wanfangdata.com.cn/index.html) and CNKI (http://www.cnki.net). These two databases provide basic information (abstracts and key words) about patents and published Master's and Ph. D. theses. Many patents related to bio-based ground improvement methods have been submitted, describing operation methods, regarding deployment and case-specific optimization or different geotechnical engineering applications, such as embankment (Xiao et al. 2017, Zhuang et al. 2012), slopes (Xie et al. 2012), retaining walls (Gao et al. 2016,), ground improvements (Du et al. 2013; Shao et al. 2015), and soil improvements (Fu et al. 2017,). The combination of bio-stabilization techniques with established methods has been investigated. For example, Gao et al. (2016) combined bio-cementation with the geogrids to provide more bearing capacity for narrow reinforced earth retaining walls. In this case, bio-mineralization could help increase the friction between the soil and geogrids.

10.6 Lessons learned and recommendations

Considering bio-based ground improvement is still a relatively new technology, no field-scale bio-stabilization project sites were visited during the scan tour and workshop in China. Still, visiting the other project sites gave insight in the potential techniques and equipment, which may be used for bio-stabilization, provided a benchmark, gave insight for which soil types and conditions bio-stabilization techniques may or may not be employed, and showed how innovations can be stimulated within an existing project. For example, one impressive project was the land reclamation site using improved vacuum preloading for about 2.528 million square meters (625 acres) in Taizhou, Zhejiang, China. Within this area, some small plots of approximate 1000 square meters (10,800 ft^2) were allotted to investigate novel techniques to improve the efficiency of vacuum drainage, such as vacuum preloading combined with electro-osmosis. Although accelerated drainage by electro-osmosis has been intensively studied, in the field it is still considered pretty new technology. Implementation was enabled by The Huadong Engineering Corporation, of China Power because they have the capacity and interest to devote time and budget to promising technologies. Another method used on this site to improve the vacuum preloading and drainage method involved applying a positive gas pressure at the center of a grid of vacuum drains, which increased the hydraulic gradient, thus improving drainage. The equipment and methods used to apply gas pressure and drain the groundwater may also be employed to inject and extract the bio-stabilization solutions. Figure 10.4 shows the test plots for improved vacuum drainage technologies, showing how innovations are implemented within a larger project. Similar methods may be used for injection and extraction of substrates for bio-stabilization.

Fig. 10.4. Test plots for improved vacuum drainage technologies.

During the presentations about the state of the art during the workshop and the discussions that followed, we learned that significant progress has been made in the research and development of bio-based ground improvement methods. While the technical feasibility of bio-based ground improvement has been demonstrated for a wide range of applications, commercial applications are still limited, due to costs, limited quality control, lack of guidelines and experience for design, and construction and quality assessment. However, field trials of these innovations may be possible when integrated within larger projects. Significant collaborative efforts of both academia and industry are still required to solve the remaining challenges to scale-up these processes towards full-scale commercial applications in geotechnical and geo-environmental engineering.

10.7 Summary

Microbially induced carbonate precipitation (MICP) by urea hydrolysis and Microbially Induced Desaturation and Precipitation (MIDP) by denitrification have been widely investigated for ground improvement applications at different scales. MICP by urea hydrolysis has been demonstrated at large-scale and several field trials have been performed for various applications, whereas MIDP still requires additional scaling efforts. Commercial application of these processes is still limited, but the path forward to adoption is being internationally actively pursued. It may take a decade or more to optimize these processes, reduce costs, improve quality control, and prepare guidelines for contractors and clients, which are essential for large scale commercial deployment.

11. OTHER TECHNOLOGIES

11.1 Introduction

The scan tour team learned other technologies from the presentations made by Chinese researchers and engineers at the 2nd China-US Workshop on Ground Improvement Technologies including (1) large-diameter cast-in-place concrete pipe piles, (2) T-shaped deep mixed columns, (3) X-shaped concrete piles, and (4) composite columns. In the following sections, these technologies are briefly discussed.

11.2 Description of the technology

11.2.1 Large-diameter cast-in-place concrete pipe piles

Large-diameter cast-in-place concrete pipe piles were developed and patented by Prof. Hanlong Liu at Chongqing University in China. Special equipment was developed to install this type of piles as shown in Figure 11.1. The diameter of the piles is typically 1.0 to 1.5 m (3.3 to 4.9 ft) and the wall thickness is 0.10 to 0.15 m (0.3 to 0.5 ft). The depth of pile installation can be as deep as 25 m (82 ft). Pile spacing typically ranges from 3.0 to 4.0 m (10 to 13 ft). Below is a typical pipe pile installation procedure:

(1) The steel casings with a specially-made pile shoe are driven into ground under vibration. The steel casings prevent soil from collapse. Concrete is placed into the annulus created by the inner and outer casings.
(2) While the steel casings are withdrawn under vibration, the concrete filled within the annulus is densified and the wall thickness is possibly increased.

The soils inside and around the pile are densified during the driving of steel casings. The range of the compacted soil depends on the properties of the soil and the thickness between the inner and outer casings. Figure 11.2(a) shows the exposed pile in the field (the inside soil was removed for the evaluation of the wall quality). The opening of the pile is covered by a concrete cap as shown in Figure 11.2(b).

This type of piles have been mostly used for embankment support for highways and railways. Liu et al. (2009) and Liu et al. (2013) documented the use of this technology and their research findings. Regional and national technical specifications were developed for the installation and design of this type of piles.

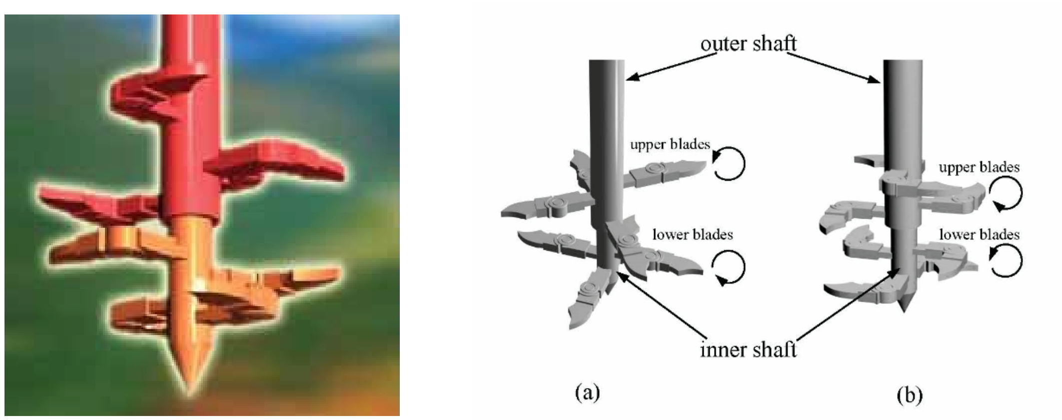
Fig. 11.1. Equipment for pipe pile installation (Liu and Kong, 2018)

(a) Exposed pipe pile (b) Covered by caps

Fig. 11.2 Pipe piles in the field (Liu and Kong, 2018)

11.2.2 T-shaped deep mixed columns

The T-shaped deep mixed column technology was developed and patented by Prof. Songyu Liu at Southeast University in China. The mixing tool developed is shown in Fig. 11.3a. It consists of a single shaft with concentric counter-rotating double tubes. The mixing blades could expand as shown in Fig. 11.3b when the rotation direction is reversed to produce larger diameter DM column at the upper portion of the DM column. The DM column installed by this mixing tool is called T-shaped deep mixing column (TDM) as shown in Fig.11.4.



(a) (b)

Fig. 11.3. DDM mixing tool (Liu, 2018)

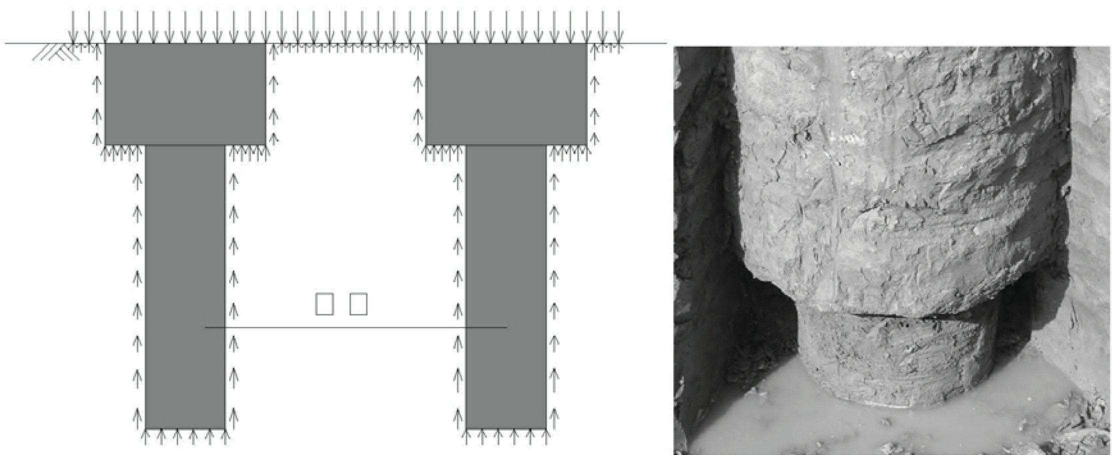


Fig. 11.4. T-shaped deep mixing column (TDM) (Liu, 2018)

The enlarged column diameter increases the area replacement ratio at the upper portion of the column, which in turn reduces the unsupported spacing between the DM columns and eliminates the need of load transfer platform between the top of DM columns and the embankment (Liu et al. 2016) as shown in Fig. 11.5. The installation procedure of TDM is illustrated in Fig. 11.6. It was reported that the TDM column could be installed to a maximum depth of 25 m (82 ft).

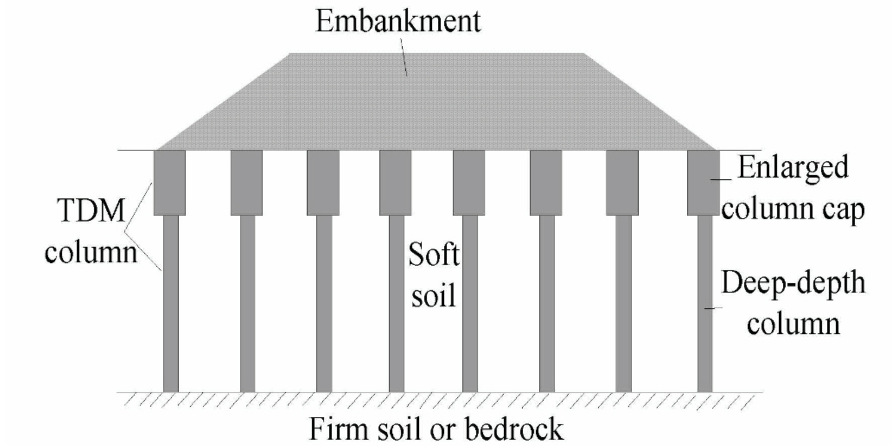


Fig. 11.5. Embankment supported by T-shaped deep mixing column (TDM) (Liu, 2018)

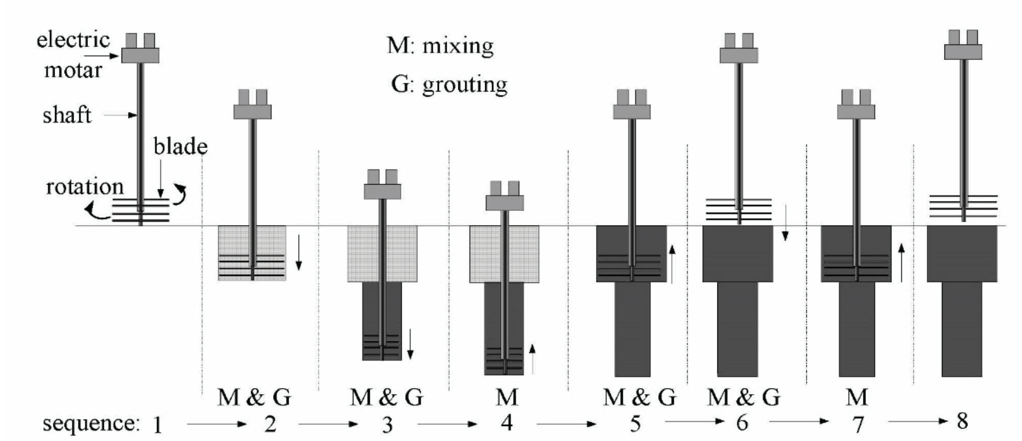
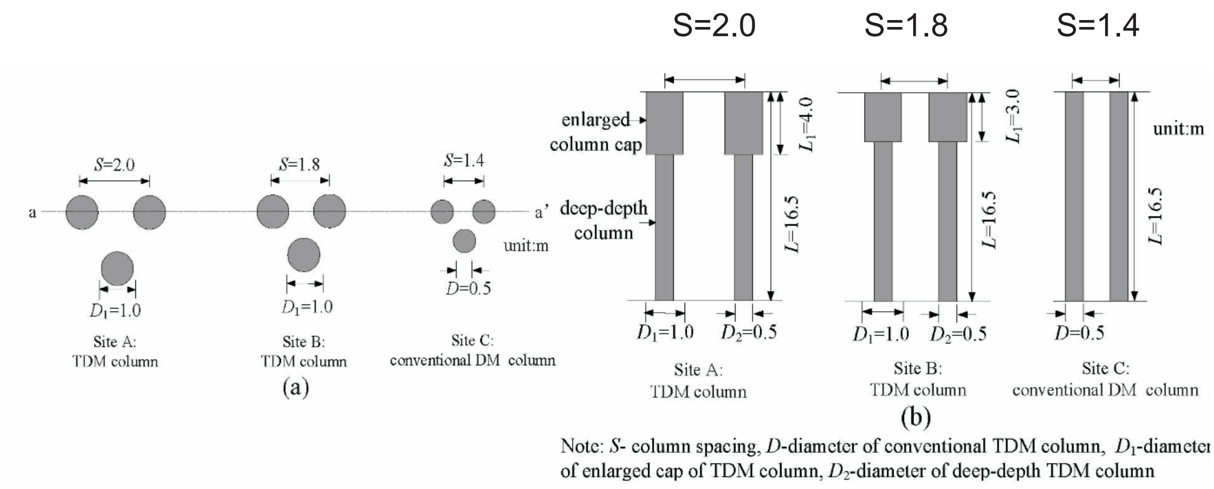


Fig. 11.6. Installation procedure of T-shaped deep mixing column (TDM) (Liu, 2018)

Field tests were conducted to compare the performance of TDM column improved ground with the performance of ground improved by conventional DM column. The test site is underlain by highly compressible clay to a depth of 14 m (46 ft) with the groundwater table at 1.0 to 2.0 m (3.3 to 6.6 ft) below existing ground surface. The plan layout and section together with column depth are shown in Fig. 11.7. Embankment, 4 m (13.1 ft) in height, was placed on two TDM column treated test sites and one conventional DM column treated test site for the study on the performance of TDM and DM treated ground.



Unit: m (1 m = 3.3 ft)

Fig. 11.7. Field test sections of T-shaped deep mixing column (TDM) and conventional DM column (Liu, 2018)

After installation of TDM and DM columns, plate load tests were performed at these three test sections. Before the placement of 4 m (13.1 ft) high embankment, pressure cells, piezometers, and inclinometers were installed to monitor the performance of the TDM and DM treated ground under embankment loading condition for 290 days. Data obtained were used to study the stress concentration ratio, excess pore water pressures generated in the soft clays, total monitored settlement, and lateral soil displacement near embankment toes. Based on the data obtained, the following conclusions were made:

- Under similar subsurface soil conditions and column strengths, the ultimate bearing capacities of TDM column treated ground are more than twice those of conventional DM column treated ground with lower area replacement ratio.
- The excess pore water pressures in the TDM column improved ground are lower than those in the conventional DM column improved ground since the efficacy of TDM columns is greater than that of DM columns and less embankment loads were distributed to the native soils between the TDM columns.
- The post-construction settlement and lateral movement under embankment toe of the TDM column treated ground were smaller than those of the conventional DM treated ground, which indicate that the TDM column treated ground performed better than the conventional DM treated ground.

The TDM column treated ground was constructed with a cement saving of 7 to 15% and construction saving of 19 to 28% than those of the conventional DM treated ground.

11.2.3 X-shaped concrete piles

X-shaped concrete piles were developed by Prof. Hanlong Liu at Chongqing University, China by changing the sectional shape of the piles from a traditional circular shape but can achieve the same bearing capacity with a reduced amount of concrete. Figure 11.8 shows the components of the installation equipment for X-shaped concrete piles. Figure 11.9 shows the equipment used in one of the actual field projects. An X-shaped hole is formed by vibrating a specially-made mandrel. The typical installation procedure is as follows: (1) the mandrel is driven into the ground by vibration, (2) the hole is filled with concrete during the withdrawal of the mandrel, and (3) pile caps are cast after the concrete is cured for a certain strength. Figure 11.10 shows two X-shaped concrete pile sections in the field.

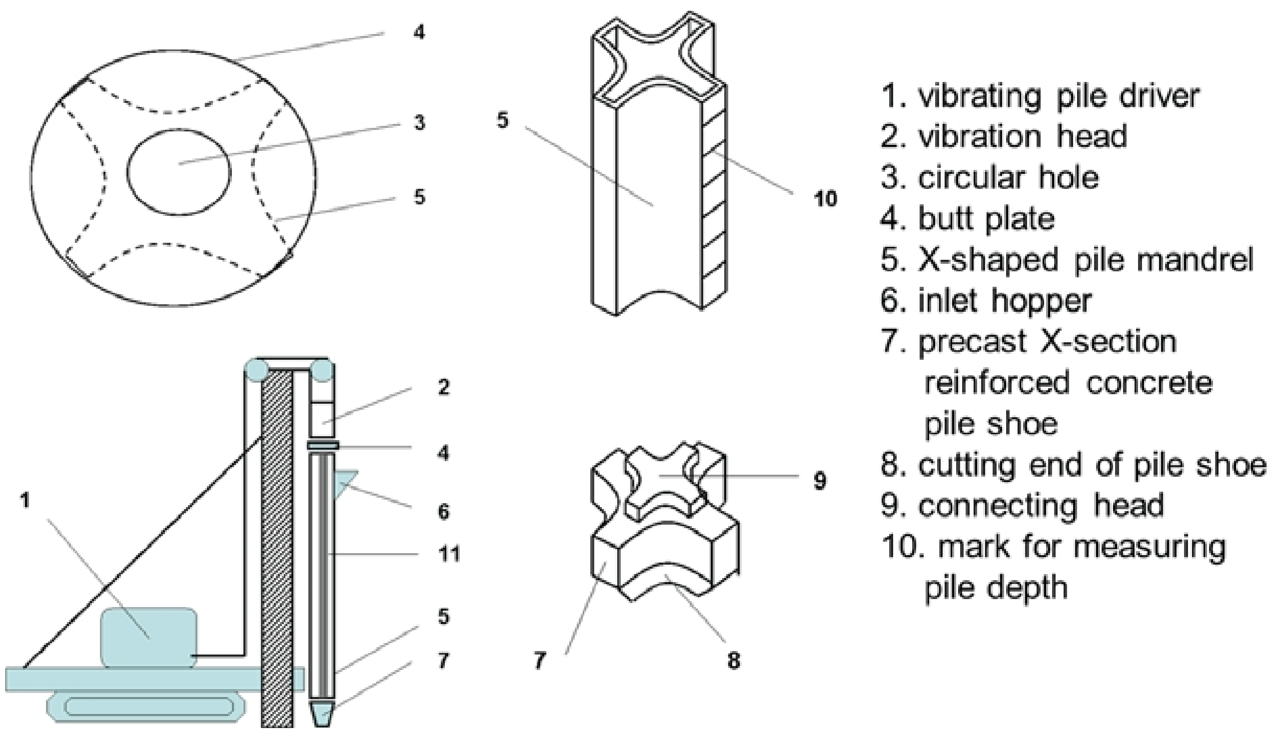


Fig. 11.8. Components of installation equipment of X-shaped piles (Liu and Kong, 2018)

Field static pile load tests showed that the X-shaped concrete piles had 16% higher load capacity if the pile length was 7.5 m (24.6 ft) or 20% higher load capacity if the pile length was 10.5 m (34.4 ft), than the circular concrete piles with the same cross sectional area (Liu and Kong, 2018). In addition to field studies, a simplified analytical model was developed to evaluate the pile installation effect in soft soil ground (Liu et al., 2014). This technology has been used for highway and roadway widening construction. Regional and national technical specifications were developed for the installation and design of this type of piles.

Fig. 11.9. X-shaped pile installation equipment used in an actual field project (Liu and Kong, 2018)

Fig. 11.10. X-shaped pile sections in the field (Liu and Kong, 2018)

11.2.4 Composite columns

With the development of column technologies in ground improvement, new composite columns have been proposed and applied in practice. Zheng et al. (2009) summarized different types of composite columns and their applications as shown in Fig. 11.11. A composite column typically contains two or three conventional columns, which are combined into one single column (Zheng et al. 2009). A composite column has one inner column installed in the middle of a large column. The inner column, with high stiffness and strength values, can stiffen the composite column. The inner column can be a deep mixed column, a grouted column, a concrete pile, or a steel pile. The outer column can be a sand column or a deep mixed column. Therefore, these columns are also referred to as stiffened columns. Based on the composition of composite columns, they can be used to increase bearing capacity, reduce total and differential settlements, and accelerate consolidation of soft foundations. They have been mostly used for embankment support for highways and railways, but sometimes also used for building or excavation support. Figure 11.12 shows two examples of composite columns in the field.

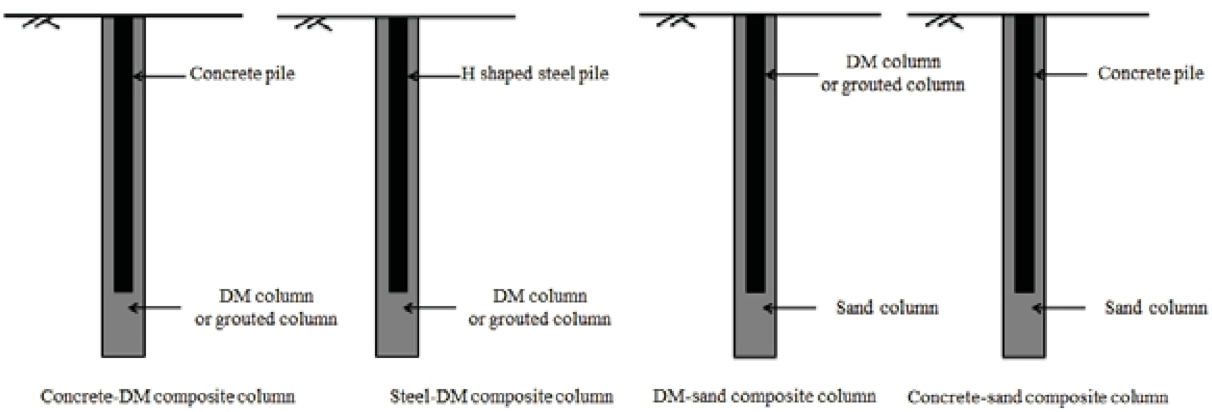


Fig. 11.11. Different types of composite columns (Zheng et al. 2009)

Figure 11.12. Examples of composite columns in the field (Zheng, 2018)

11.3. Project site

No project site was visited related to the above technologies during this scan tour. The above technologies have been mostly used to improve soft soils for embankment support for highways and railways. Equipment for each technology was developed with special features. The design of the columns installed by these technologies follows the theory of composite foundations.

11.4. Research work and key findings

After the development of the technologies, a series of research was conducted for each technology by the developer and his research group. Research work and key findings have been mostly published in journals and conference proceedings in China, but some of them have been published in international journals and conference proceedings in English. Extensive review of these publications have not been conducted. Based on limited publications reviewed, each technology has pile load test data, field installation and monitoring data, design guidelines, and regional and/or national specifications. Below are a few of key findings:

(1) Use of shaped piles or columns reduces the amount of cement or concrete to achieve the same load carrying capacity as conventional circular columns thus reducing the cost of construction.
(2) Use of T-shaped deep mixed columns can increase the spacing of columns.
(3) Use of rigid piles in large columns can effectively utilize the advantages of both components and significantly increase vertical and lateral load carrying capacities.

11.5. Identified innovations if any

The key innovations in these technologies are the development of new installation equipment and the idea of utilizing different shapes of columns or combining different pile/column systems.

11.6. Lessons learned and recommendations

The concepts of these technologies are interesting and theoretically sound. Rate of installation is unknown. Quality control and assurance may be challenging and deserve further investigation. These technologies are recommended for further research in the US before they are adopted for actual projects

The expandable blade design enables the construction of T-shaped deep mixing column (TDM) to reduce the total number of deep mixing columns while maintaining the required area treatment ratio to eliminate the need of using a load transfer platform. The development of this soil mixing equipment improves the quality of soil mixing column and reduces the construction time and cost.

11.7. Summary

China researchers have developed different column systems using innovative ideas by changing the shape of columns or combining different columns into one column. These technologies are mostly used in soft soils to support embankments and show some technical and economic benefits. All these technologies have regional and/or national specifications.

12. CONCLUSIONS, KEY OBSERVATIONS, AND RECOMMENDATIONS

12.1 Conclusions and Key Observations

This report documents the ground improvement technologies learned from the scan tour and the 2nd China-US Workshop on Ground Improvement Technologies. The following conclusions and recommendations can be made:

(1) The techniques and equipment used to install the diaphragm walls in China are similar to those in North America. The diaphragm walls have been successfully constructed in China deeper than 100 m (330 ft). A comprehensive joint sealing system against water inflow has been developed employing ground freezing and grouting.
(2) Dynamic compaction has been successfully used with vacuum dewatering in China to improve saturated silty soils. Vacuum dewatering not only lowers the groundwater table before dynamic compaction but also dissipates excess pore water pressure after dynamic compaction.
(3) Ground anchors have been installed by jet grouting in China. This technology allows the recovery of anchor strands at the end of construction to minimize construction cost and environmental impact. Jet grouting can enlarge the anchor equivalent bond diameter and increase the anchor load capacity in medium stiff clays.
(4) The methods and equipment used for deep soil mixing are similar to those in North America. The special equipment used to install T-shape deep mixed columns in China is an innovation, which can reduce column spacing and increase bearing capacity near the surface, thus creating a more effective and economic solution for embankment support.
(5) The surface soft soil stabilization method by shallowly mixing soil with binder to create a working platform on soft soil is similar to that used in North America.
(6) Vacuum preloading has been successfully and commonly used in China to improve large reclaimed land with dredged silt and clay. Several innovations have been made, such as the specially-designed PVDs to minimize bending and clogging, the improved connector between PVDs and vacuum hose, the powerful and efficient vacuum pump to separate air from water, and the positive pressure soil sparging technique to increase hydraulic gradient for water drainage.
(7) The electro-osmosis enhanced PVD consolidation technology with PVDs has been developed and tested in China, which shows promising results. However this technology still has some limitations, such as labor-intensive installation, high cost, and degradation of electrical conductivity with time. The cost may be offset by the shortened time for consolidation as this technology can drain water faster than conventional PVDs plus preloading. In addition, solar panels potentially can be used to supply power and this option is now being explored in China.
(8) Bio-based ground improvement is still a relatively new technology in China. Several research groups have been working on this technology in the past few

years. The first bio-based geotechnical engineering conference was held in China in October 2018. It is expected that more research results on this technology will be presented by Chinese researchers in the near future.

(9) Chinese researchers and engineers have developed equipment and techniques to produce and/or install special shape piles or columns, including bamboo-shaped prestressed precast concrete piles, large-diameter cast-in-place concrete pipe piles, x-shaped piles, and composite columns to facilitate load transfer and reduce material cost.

12.2 Recommendations

The field observations, publications, and findings obtained on recent innovations and developments of ground improvement technologies from the scan tour may be used to update the GeoTechTools. The scan tour team would like to make the following recommendations:

(1) To include the large project for Suzhou River Deep Drainage and Storage Facility in Shanghai as a case history, highlighting the important facts of the 105-m (344-ft) deep excavation and the comprehensive joint sealing system,

(2) To include the combined dynamic compaction with vacuum dewatering technology as special measures to improve saturated silty soils using dynamic compaction,

(3) To include the technology using jet grouting to install ground anchors with the recoverable anchor strands and wide flange beams approach to reduce construction cost and environmental impacts in the ground anchors technology,

(4) To add the method for installing and using T-shaped deep mixed columns for embankment support in the deep soil mixing technology,

(5) To expand the section of vacuum preloading with several key innovations, developments, and applications in China,

(6) To add the recent developments in electro-osmosis dewatering/consolidation technology with PVDs in the electro-osmosis technology, and

(7) To add a new technology with the recent innovations, developments, and applications of shaped columns and composite columns.

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- The Architectural Design and Research Institute of Zhejiang University Co., Ltd.
- Huadong Engineering Co. Ltd.
- Zhejiang Geofore Geotechnical Engineering Co., Ltd.
- China Railway Construction Co.
- Hangzhou Metropolitan Expressway Co., Ltd.
- Zhejiang Communication Investment Group Co., Ltd.
- Hangzhou Shenyuan Environmental Sci-Tech Co. Ltd
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APPENDIX

The following proceedings of abstracts were distributed at the 2nd China-US Workshop on Ground Improvement Technologies held in Shanghai, China on May 27th, 2018.

The Second China-US Workshop on Ground Improvement Technologies

Organized by

Chinese Institution of Soil Mechanics & Geotechnical Engineering

ASCE Geo-Institute Soil Improvement Committee

Edited by

Jie Han, Gang Zheng, Yuanqiang Cai, Jose Clemente, Shuilong Shen, Guanbao Ye, and Lisheng Shao

Shanghai, China, May 27th, 2018

Workshop Organization

Organized by: Chinese Institution of Soil Mechanics & Geotechnical Engineering and ASCE Geo-Institute Soil Improvement Committee

Hosted by: Tongji University, Tianjin University, Zhejiang University of Technology, and Shanghai Jiaotong University, China

Sponsored by: Tongji University and ASCE Geo-Institute

Chairs: Gang Zheng, Professor, Tianjin University, Tianjin, China

Jie Han, Professor, the University of Kansas, USA

Organizing Committee

Prof. Yuanqiang Cai, Zhejiang University of Technology, China

Dr. Jose Clemente, Bechtel, USA

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Secretary: Dr. Zhen Zhang and Ms. Panpan Shen, Tongji University, China

Preface

The ASCE Geo-Institute Soil Improvement Committee and the Chinese Institution of Soil Mechanics and Geotechnical Engineering jointly organized the first US-China Workshop on Ground Improvement Technologies in Orlando, Florida, USA on March 14, 2009. After this workshop, the ASCE Geo-Institute and the Chinese Institution of Soil Mechanics and Geotechnical Engineering signed a cooperative agreement between these two institutions to promote technical cooperation and exchange among researchers and engineers between these two great countries. In the past ten years since the last workshop, ground improvement technologies have been advanced and new technologies have emerged. The ground improvement community in China and the US found it very beneficial to jointly organize the Second China-US Workshop on Ground Improvement Technologies in Shanghai, China on May 27th, 2018. This workshop strengthened the relationship between researchers and engineers in these two countries, provided them the opportunities to exchange information and knowledge on recent developments and advancements in ground improvement technologies, and offered a forum to discuss and debate future directions for ground improvement in the 21st century. These proceedings include the extended abstracts of all the technical presentations made at the Second China-US Workshop on Ground Improvement Technologies.

Before this workshop, the US delegate consisting of researchers, consultants, and contractors had a technical scan tour to six project sites in Shanghai and Zhejiang Province, China, where different ground improvement technologies were adopted. The scan tour was proposed by the ASCE Geo-Institute Soil Improvement Committee led by Dr. Kord Wissmann (past chair) and Prof. Jie Han (current chair) with the strong support from Dr. James Collin (governor) and approved/sponsored by the ASCE Geo-Institute. The US delegate appreciated very much the Chinese counterparts for providing great hospitality and technical demonstration/information on different ground improvement technologies on the tour.

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Presentation title and speaker **Page number**

Recent developments of ground improvement technologies in China

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Abstract

To date, the ground improvement technology is one of the most active fields in geotechnical engineering in China. In recent years, ground improvement technologies have been developing from a single technique to a combined technique. The *Chinese Technical Code for Ground Treatment for Buildings JGJ 79 – 2011* (China Building Research Institute, 2011) summarized typical ground treatment methods including the preloading, dynamic consolidation, and composite foundations. Based on these methods, a series of newly combined techniques have been developed, such as vacuum - surcharge preloading, electro-osmosis and vacuum preloading, and rigid-flexible piles composite foundations, as shown in Table 1.

Table 1. Typical ground improvement methods in China

	Category	Typical methods
Single technique	cushion	unreinforced cushion reinforced cushion
	preloading	surcharge preloading vacuum preloading
	dynamic consolidation	dynamic compaction
	compaction	vibro-replacement
	composite foundation	stone columns cement-flyash-gravel piles rammed soil-cement piles cement deep mixing chemical churning piles lime-soil piles
	injection	—
	mini piles	—
Combined techniques	vacuum-surcharge preloading vacuum-dynamic consolidation underwater vacuum preloading electro-osmosis and vacuum preloading electro-osmosis and vacuum preloading and low-energy dynamic consolidation rigid-flexible piles composite foundation long-short piles composite foundation	

Often, several ground improvement methods, including vacuum-surcharge preloading, dynamic compactions, composite foundations with various column type technologies, and pile-net composite foundations, are used simultaneously in one project (e.g., the construction of highways and railways) in China.

For composite foundations, rigid piles are intensively adopted for the rapid construction of embankments. However, failure case histories sometimes occurred and few studies have examined rigid piles (Han, 2014). Kitazume and Maruyama (2006; 2007) categorized the shear and bending failure as the internal stability, and they considered the sliding and tilting failure as the external stability. For the internal stability of rigid piles, Zheng et al., (2010; 2012) numerically and experimentally reported that a primary bending failure occurs at the interface of soft and hard strata, followed by a secondary bending failure within the upper part of the rigid piles, resulting in a global instability of embankments. Zheng et al., (2018) recently revealed a progressive phenomenon for rigid piles. Specifically, pile rupture releases stress and causes a significant increase in the tensile stress within neighboring piles, possibly leading to a continuous failure of adjacent piles. Therefore, conventional design methods based on a simultaneous failure assumption may overestimate the stability. For the external stability, the tilting failure of piles has been previously reported when piles are seated on top of an underlying firm stratum. For piles with a certain embedded depth L_e, ranging from 0 to $2.5D$ (D = the diameter of piles), a bending failure was commonly observed for horizontal underlying stratum in previous literatures. In China, an embedded depth $L_e = 2.0D$ has often been used in engineering design. However, an inclined underlying stratum is commonly encountered in reality. Zhou et al., (2018) reported a failure case history of embankments above soft ground with an inclined underlying stratum. Based on centrifuge tests, they demonstrated that a tilting failure occurs for $L_e = 2D$ as the inclined underlying firm stratum weakens the embedding effect of the piles. In that situation, the piles cannot fully develop their bending capacity when the embankment failed. Thus, a greater embedment depth is required and the adverse impact of inclined underlying stratum should be considered.

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Bio of Speaker

Prof. Gang Zheng, is a Professor at Department of Civil Engineering at Tianjin University, P.R. China. He serves as the Dean of School of Civil Engineering of Tianjin University and was the Head of Department of Civil Engineering from 2003 to 2009. He was elected as Changjiang Scholar in 2015 by Ministry of Education, China.

Prof. Zheng is the vice president of the Chinese Institution of Soil Mechanics and Geotechnical Engineering (CISMGE). Prof. Zheng is the member of TC204, ISSMGE (Technical Committee of Underground Construction in soft ground) and was the member of TC17, ISSMGE from 2007 to 2011.

He received his Master degree in 1992 and Ph.D. degree in 2000 in Civil Engineering from Tianjin University. He was a visiting scholar to Cambridge University from 2004 to 2005.

Prof. Zheng's research and practical experiences has specialized principally in deep excavation, ground improvement, pile foundations, shield tunneling.

Prof. Zheng has co-authored one technical books, edited one ASCE Geotechnical Special Publications, and published more than 210 peer-reviewed journal papers and about 30 conference papers, including more than 50 international journal papers and international conference papers.

Prof. Zheng serves as a member on the editorial boards for three major national journals in civil and geotechnical engineering and one international journal.

Prof. Zheng has been invited more than 30 times as keynote speaker of national conferences and 4 times as keynote speaker or invited lecture speaker of international conferences.

Prof. Zheng received the 2013 R.M. Quigley Award by the Canadian Geotechnical Society for the best paper in the Canadian Geotechnical Journal in 2012. ("Excavation effects on pile behavior and capacity" by G. Zheng, SY Peng, CWW Ng and Y Diao). Prof. Zheng also received the Award of Young Geotechnical Expert of Mao Yisheng Soil Mechanics and Geotechnical Engineering in 2010. He has won the second prize of National Scientific and Technological Progress Award for 1 time, the first prize of Scientific and Technological Progress Award of Ministry of Education and the first prize of Scientific and Technological Progress Award of Tianjin Municipal Government for one time respectively.

Recent Developments of Ground Improvement Technologies in the US

Jie Han[1]

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Recent Developments

In the past ten years, there have been a few important developments in ground improvement technologies in the United States. Based on the survey with several experts in the field of ground improvement research and practice, below are a few recent important developments (please note: the list provided is neither necessarily complete nor in the order of importance):

1. Ground improvement concept or method
   - intelligent compaction technologies
   - closely spaced geosynthetic-reinforced soil (GRS) for support of structures
   - lightweight fill (e.g., foamed glass, foamed concrete)
   - increased use of rigid inclusions (e.g., displacement piles)
   - Slope Reinforcement Technology (SRT) slope repair
   - hollow-bar soil nails
   - wicking geotextile for soil moisture reduction
   - research on bio-mediated and bio-inspired ground improvement technologies
2. Theory/design method
   - design of geosynthetic-reinforced column-supported embankment
   - liquefaction mitigation analysis by stiff elements and walls
   - reliability-based design for stone columns and micropiles, etc.
   - stabilization of slopes with micropiles using soil structure interaction and mobilization of resistance based on deformations
   - mechanistic-empirical design of geosynthetic-stabilized roads
   - Limit equilibrium design framework for MSE structures with extensible reinforcement
3. Equipment
   - intelligent compaction rollers
   - advancements in data acquisition (DAQ) systems
   - automated rig and pump controls
   - on-rig GPS capability, tooling advancements
   - jet grout monitor advancements
   - low disturbance piling/sheetpiling equipment
   - bigger vibrators
4. Construction technique
   - intelligent compaction
   - high-energy compaction
   - use of automatic equipment and control, and DAQ
5. QA/QC
   - performance-based specification

- intelligent compaction with response measurements
- DAQ
- better coring techniques
- geophysical methods for site characterization

6. High-impact project, event, or publication
   - Strategic Highway Research Program 2 (SHRP II) R02 project – GeoTech Tools (approximately 8,000 registered users worldwide)
   - Center for Bio-mediated and Bio-inspired Geotechnics – sponsored by US National Science Foundation
   - FHWA Every Day Count (EDC) Program for Geosynthetic Reinforced Soil-Integrated Bridge System
   - Ground Modification Methods Reference Manual Vols. I and II (FHWA-NHI-16-027 and FHWA-NHI-16-028)
   - Soil Nail Walls (FHWA-NHI-14-007)
   - Geosynthetic Reinforced Soil Integrated Bridge System Interim Implementation Guide (FHWA-HRT-11-026)
   - Limit Equilibrium Design Framework for MSE Structures with Extensible Reinforcement (FHWA-HIF-17-004).

Future Trends and Needs

These experts also offered their opinions on the trends and needs for ground improvement research and practice in next 10 years:

1. Ground improvement research
   - liquefaction triggering and mitigation (especially for silts) including refinements in cyclic stress redistribution and effect of internal stability / strains due to flexure of rigid inclusions during cyclic shear
   - displacement piling for liquefaction/lateral spreading
   - carbonate precipitation for soil improvement
   - bio-film generation and propagation
   - bio-inspired ground anchors and soil nails
   - QA methods (e.g., requirements for acceptance and payment)
2. Ground improvement practice
   - decision making and risk management (providing guidance and procedures on proper selection of a ground improvement solution, and providing more proactive opportunities for geotechnical interaction)
   - acceptance of liquefaction mitigation analysis by stiff elements and walls
   - better practice and application of numerical modeling
   - better quality control measures and standardization
   - more update and improvement of equipment
   - field trials and adoption of bio-mediated and bio-inspired ground improvement technologies in the practice.

Brief Descriptions of Two Technologies

This presentation will focus on two ground improvement technologies as examples to demonstrate the new developments of these technologies.

Geosynthetic-reinforced soil-integrated bridge system (GRS-IBS) as shown in Figure 1 has been increasingly used in the US. This system consists of closely-spaced reinforcement layers in the reinforced fill to support bridges without any pile foundations. This system can effectively eliminate bump at the end of a bridge. Because of its benefits, the GRS-IBS was selected for deployment through the Federal Highway Administration's (FHWA's) Every Day Counts (EDC) initiative in 2010. Over 200 bridges in 44 states have been constructed in the US using GRS-IBS since 2010. Adams et al. (2012) provided the implementation guide for the GRS-IBS.

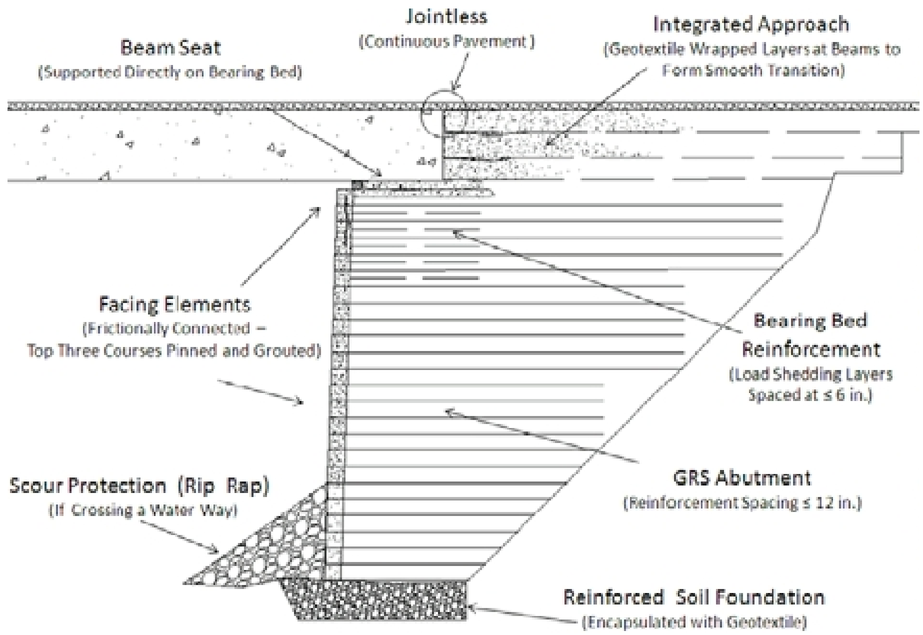

Figure 1. Typical GRS-IBS cross section

It is well recognized that water has detrimental effects on roadway performance due to the increase of soil weight, expansion-shrinkage, and freeze-thaw potential and the reduction of soil strength and modulus. Reduction of soil moisture can improve the roadway performance, often through drainage and dewatering, which require saturation of soil and hydraulic gradient. However, soil in roadways may not always be saturated. Even under partially saturated conditions, soil may have too high moisture content that is still problematic to roadway performance. An innovative geotextile product (named the wicking geotextile) recently introduced into the market has deep-groove fibers (Figure 2) with large surface areas that can generate capillary or suction force to suck water into the fibers when they are in contact with water. The sucked water can be transported to the exposed surface of the geotextile and evaporate into air due to the relative humidity difference between the wet geotextile and air. This process continues until the suction in the fibers is equal to that in the soil. This presentation will discuss on the detrimental effects of water to roadway performance, explain the functions of wicking geotextile, and present a couple of experimental tests (Han et al., 2018). This presentation will discuss the design guidelines for considering the benefits of the wicking geotextile in improving paved roads. One case study will be presented using the wicking geotextile to eliminate freeze-thaw problems in an unpaved road.

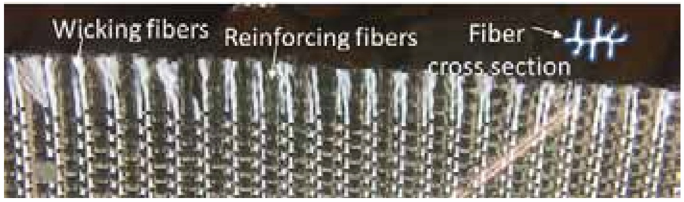

Figure 2. Wicking Geotextile

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Acknowledgement

The author would like to express his appreciation to the following individuals who offered their experts' opinions on the recent developments of ground improvement technologies in the United States: James G. Collin, James D. Hussin, Edward Kavazanjian, Silas Nicholas, Vernon Schaefer, Lisheng Shao, and Armin W. Stuedlein.

Bio of Speaker

Dr. Jie Han is the Glenn L. Parker Professor of Geotechnical Engineering in the Civil, Environmental, and Architectural Engineering Department at the University of Kansas. He received his BS and MS degrees from Tongji University in China and his Ph.D. degree from the Georgia Institute of Technology in 1997. His research has focused on geosynthetics, ground improvement, pile foundations, buried structures, and roadways. Prof. Han is the sole author of the book entitled "Principles and Practice of Ground Improvement" and has published more than 300 peer-reviewed journal and conference papers. Prof. Han is the chair of the ASCE Geo-Institute Soil Improvement Committee. He serves as an associate editor for the ASCE Journal of Geotechnical and Geoenvironmental Engineering and the ASCE Journal of Materials in Civil Engineering and as an editorial board member for ten other international journals. Dr. Han has been invited to give more than 200 keynote/invited lectures and short courses around the world. He has received numerous awards from the profession including but not limited to two US Transportation Research Board Best Paper Awards in 2008 and 2017, the 2011 Shamsher Prakash Prize for Excellence in Practice of Geotechnical Engineering, the 2014 International Geosynthetics Society (IGS) Award, the 2014 Associate Editor of the Year Award from the ASCE Journal of Geotechnical and Geoenvironmental Engineering, and the 2017 ASCE Martin S. Kapp Foundation Engineering Award. Dr. Han was elected to the ASCE Fellow in 2014.

US Practice – Load resistance factored design of soil nail walls

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Introduction

This presentation will provide guidance for the design and construction of soil nail walls based on the FHWA Soil Nail Design Manual. The manual provides guidance on the following topics:

- Implementation of the Load and Resistance Factor Design (LRFD) platform
- Design considerations for hollow bars used as soil nails (HBSNs)
- Incorporation of more thorough corrosion criteria for soil nail design

The definition of a soil nail incorporates the following fundamental elements: resisting mechanisms, materials, construction methods, and construction Quality Control (QC) and Quality Assurance (QA).

Soil nails are reinforcing, passive elements that are drilled and grouted sub-horizontally in the ground to support excavations in soil, or in soft and weathered rock that:

- Contribute to the stability of earth-resisting systems mainly through tension as a result of the deformation of the retained soil or weathered rock mass.
- Transfer tensile loads to the surrounding ground through shear stresses (i.e., bond stresses) along the grout-ground interface.
- Develop resistances that can be estimated with established design procedures.
- Have long-term, demonstrable corrosion protection to ensure adequate, long-term performance of the system.
- Interact structurally with the facing of the excavation.
- Are load-tested according to prescribed methods.
- Are routinely subject to construction QC/QA according to established procedures.

Reinforcing elements that are post-tensioned, even if installed adjacent to conventional soil nails, are referred to as ground anchors, which are not addressed in the FHWA Soil Nail Design Manual. Information on ground anchors can be found in Article 11.9 of AASHTO (2014) and “Ground Anchors and Anchored Systems,” Geotechnical Engineering Circular No. 4, Report No. FHWA-IF-99-015 (Sabatini et al. 1999).

As stated in the definition, load transfer to and from the surrounding ground develops through shear stresses acting along the grout interface of the soil nail. As the reinforced-soil block deforms, shear stresses develop at the grout-ground interface. Because the retained soil deforms toward the excavation, soil nails undergo extension resulting in axial tensile forces in the soil nail tendon. The axial tensile load in the tendon increases from the nail head to a maximum value; then decreases as the soil nail transfers load to the surrounding ground. The tensile resistance of the soil nail tendon and the pull-out resistance of the soil nail are the main resisting mechanisms.

Developments in the United States

One of the first applications of this technology in the U.S. was in 1976 when soil nails were used to provide support to a 45-ft deep excavation made in lacustrine, dense, silty sands for the expansion of the Good Samaritan Hospital in Portland, Oregon. It was estimated that this system was completed in nearly half the time and at about 85 percent of the cost of conventional excavation-support systems (Byrne et al. 1998). In 1984 FHWA funded a demonstration project for the installation of a prototype, 40-ft high soil nail wall near Cumberland Gap, Kentucky (Nicholson 1986).

Since its introduction in the U.S., the use of soil nail walls has increased greatly for roadway projects. This increase can be attributed to the technical feasibility and cost-competitiveness of soil nailing. For certain subsurface and project conditions, soil nailing is more advantageous than other top-down, earth retaining systems because the construction equipment is smaller, and it provides greater structural redundancy (i.e., a larger number of reinforcing elements per unit of wall area than other systems). Easements tend to be smaller for soil nail projects because soil nails are shorter than ground anchors, for example, given the same wall height. Additionally, as the use of soil nailing has grown, the number of qualified, soil-nail specialty contractors has increased. The project experience gained among engineers and Owners, especially state transportation agencies, has also increased over the years.

Design Philosophy

The US design philosophy consists of a framework that allows the designer to:

- Verify structural capacities in the conventional LRFD equation format, using load factor values from the AASHTO "LRFD Bridge Design Specifications" (2014).
- Utilize conventional Allowable Stress Design (ASD)-based, limit-equilibrium, computer programs developed specifically for designing soil nail walls to determine nominal loads in soil nail wall components (Figure 1).

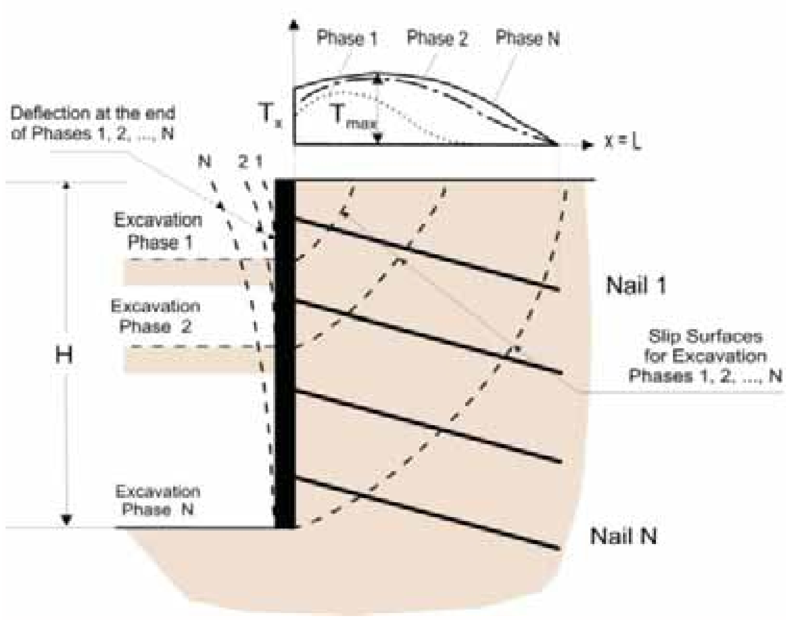

Figure 1. Limit Equilibrium Analysis

- Incorporate resistance factors correlated to load factors included in AASHTO (2017) that would result in designs that are equal to or slightly more conservative than designs developed through ASD-based factors of safety (FS) as defined in previous versions of this manual.
- Incorporate correlated resistance factors that are rounded to the closest 0.05 and are reasonable and compatible with, but not necessarily equal to, those presented in AASHTO (2014) for other earth-retention structures and corresponding limit states.
- Incorporate correlated resistance factors that are consistent with a minimum required frequency of verification testing.

Therefore, the soil nail wall design relies on ASD-based stability calculations to quantify soil nail loads and slip surface geometries, and then uses these results to perform LRFD checks. The LRFD framework contained in this manual considers service, strength, and extreme-event limit states, consistent with those of AASHTO (2017).

Bio of Speaker

Dr. James Collin is the president of the Collin Group, Ltd and currently serves as the governor of the ASCE Geo-Institute. He received his Ph.D. degree from the University of California, Berkeley in 1985. He was author of the National Highway Institutes "Ground Improvement Methods Manual," "Soil Slope and Embankment Design Manual", "Slope Maintenance and Slide Restoration", and "Shallow Foundations Manual". Dr. Collin is also a certified instructor for the U.S. DOT, Federal Highway Administration courses on Ground Improvement, Geosynthetic Design and Construction Guidelines, Shallow Foundations, Soil Slopes and Embankments, Earth Retaining Structures, MSEW and RSS Design and Construction Guidelines, Slope Maintenance and Slide Restoration, and Geosynthetics. He was recognized by NHI as an "Instructor of Excellent" for 2008, 2009, and 2011. Dr. Collin has led the use of column-supported embankments on load transfer platforms in the United States. He was part of a team that developed the FHWA Design Manual on Deep Mixing for Embankment and Foundation Support. Dr. Collin was one of the principal investigators for the SHRP2R02 project on "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform." Dr. Collin has served as an expert witness for over 100 geotechnical and or construction related failures both in the US and abroad. He was the recipient of the Wallace Hayward Baker Award in 2013.

Jet grouting: Recent 14 years' research and practice in Shanghai Jiao Tong University

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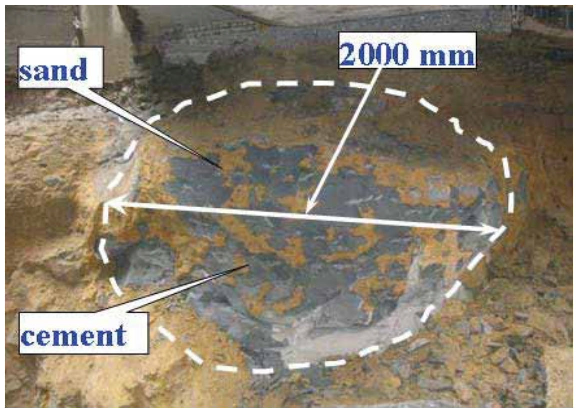
Abstract

This presentation introduces the recent 14 years' research and practice of jet grouting in Shanghai Jiao Tong University (SJTU), including both technological development and scientific research. Technological development included field investigations of Rodin jet grouting (RJP), Twin-jet grouting from development of construction machine and field testing constructions, low impact jet-grouting technologies (Composite-pipe method and Pressure controlled method). RJP is a double high pressure jet grouting, which can create a diameter of column over 2 m in the soft deposit of Shanghai. RJP can get high quality column in clayey soil whereas the quality of RJP in sandy soil is poor due to bleeding. Twin-jet method uses two binders to create jet grouted column and makes column quick gelling within several second, which can overcome the poor quality of jet-grouted column in sandy soil (Shen et al., 2013a). Low impact jet-grouting technologies was developed to reduce the surrounding impact during jetting (Wang et al., 2013). There are two types of low impact jet-grouting technologies: composite-pipe method and pressure controlled method. Composite-pipe method added a pipe to remove spoil within the rod, which makes the rod becomes heavier than original and reduced the construction efficiency due to rod change (Shen et al., 2013b). Pressure controlled method was designed to remove spoil outside the rod, which was created from the gap between the monitor (enlarged diameter) and rod (Wang et al., 2014). Figure 1 shows the column quality from RJP, Twin-jet, principle of low impact jet-grouting technologies.

The scientific researches includes two aspects: prediction method of diameter of jet-grouted column and ground deformation. A generalized approach for predicting the diameter of jet grout columns based on the theoretical framework of turbulent kinematic flow and soil erosion was proposed (Shen et al., 2013c). The proposed calculation method is applicable to all conventional jet-grouting systems and takes into account the full range of operational parameters, fluid properties, soil strength, and particle size distribution, including the effect of the injection time on erosion distance. The proposed method was applicable four variants of jet-grouting systems, i.e., single fluid, double fluid, triple fluid, and an enhanced triple fluid system. The proposed generalized approach allows all the key variables to be considered and is a useful means for the design of ground improvement by jet grouting.

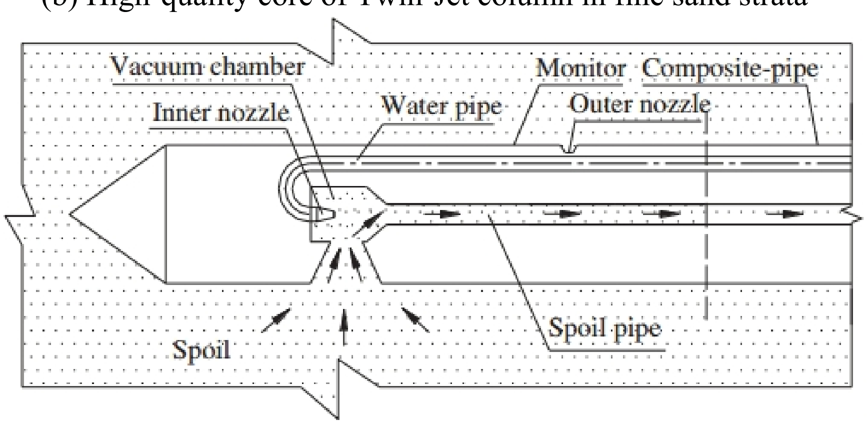
An approach to estimate the lateral displacement due to the installation of a jet-grouted column in clayey soils was proposed to predict the installation impact of jet-grouted columns in soft ground. Assuming that the installation of a jet-grouted column is represented by the expansion of a cylindrical cavity with a uniform radial stress applied at the plastic–elastic interface in a half-plane, the analytical solution developed by Verruijt is

adopted in this study to calculate the lateral displacements attributable to the expansion of the cylindrical cavity. An empirical equation that accounts for the jetting parameters (jetting pressure, flow rate of the fluid and rod withdrawal rate) and soil properties (soil type and its undrained shear strength) has been developed to determine the radius of the plastic zone (Shen et al., 2017). Three case histories analysed in this paper demonstrate that the proposed method can be used for estimation of the lateral displacement caused by installing jet-grouted columns in clayey soils, despite minor discrepancies from the group column installation case between the predicted and measured values.



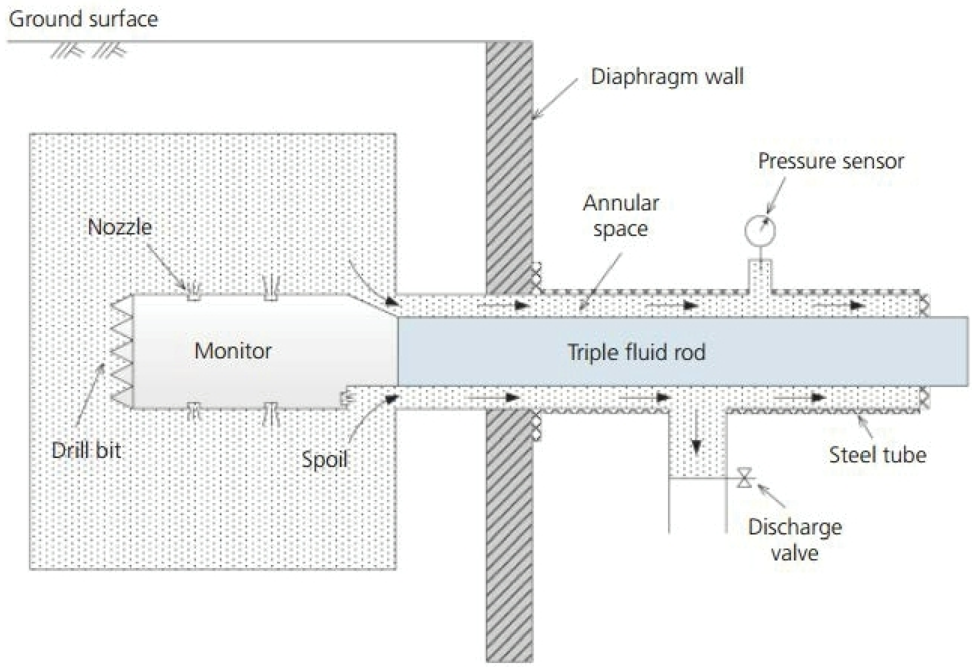
(a) Poor quality column of RJP in silty sand strata

(b) High-quality core of Twin-Jet column in fine sand strata



(c) Illustration of composite-pipe monitor and moving of spoil

Figure 1. Column quality and low impact jet-grouting technologies



(d) Pressure controlled method

Figure 1. Column quality and low impact jet-grouting technologies (continued)

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Bio of Speaker

Prof. Dr. Shui-Long Shen received his Bachelor of Science in Civil Engineering from Tongji University in 1986 and his MSc in Structural Engineering from the same university in 1989. He obtained his PhD. in Geotechnical Engineering from Saga University, Japan, in 1998.

After Dr. Shen received his PhD, he worked in the Institute of Lowland Technology (ILT) as a lecturer from 1998 to 2001. During this period Dr. Shen served as an Associate Editor of Lowland Technology International-an International Journal. From 2001 to 2003, Dr. Shen worked in National Institute for Environmental Studies in Tsukuba-the Science City, Japan. In 2003, he joined the Department of Civil Engineering (DCE) of Shanghai Jiao Tong University (SJTU) as a faculty member. He is now the Department Head of DEC, SJTU. From 2005 to 2018, Dr. Shen has been keeping collaboration with other international organization, e.g., Saga University, Virginia Tech, The University of Kansas, The University of Hong Kong, Suranaree University of Technology Thailand, Ecole Centrale de Nantes France, Swinburne University of Technology, Royal Institute of Technology, Australia as a guest/visiting/adjunct professors.

Dr. Shen's research interests focus on groundwater control induced by underground construction, soft soil improvement, tunneling. He published/edited six books, of which three conference proceedings published by ASCE. Dr. Shen published more than 300 technical papers in Journals and International conferences, in which over 150 papers were published in International Journals with total citation over 3500 times. Eight ESI highly cited papers (top 1%) form Journal citation report in March 2018. Dr. Shen's H-Index in SCOPUS is 35, in Web of Science is 32. Dr. Shen also serves as an Editor/Editorial board member of following International Journals, e.g., Canadian Geotechnical Journal, Geotextiles and Geomembranes, Computers and Geotechnics, Elsevier; Marine Georesources and Geotechnology, Taylor and Francis; Frontiers of Structural and Civil Engineering; Lowland Technology International, and Geotechnical Engineering – SEAGS etc. and domestic journals, e.g. Chinese Journal of Geotechnical Engineering.

High Mobility Grouting for Dams and Tunnels

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[1]Chief Engineer, Hayward Baker, Inc. Western Region

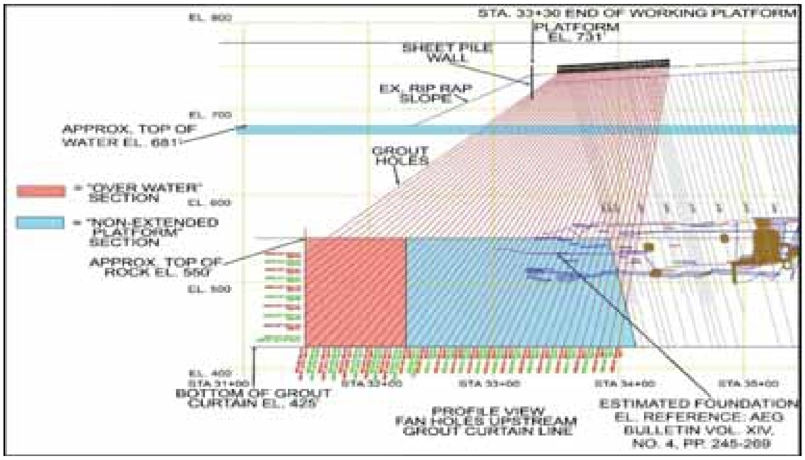
Abstract

High mobility grouting (HMG) includes permeation, fracture grouting, slurry grouting, etc., and has been used for various projects for dams, tunnels, and building foundations. This presentation provides an outline of these grouting technologies, equipment and measurement devices, and their applications for tunneling, dam cut-off walls.

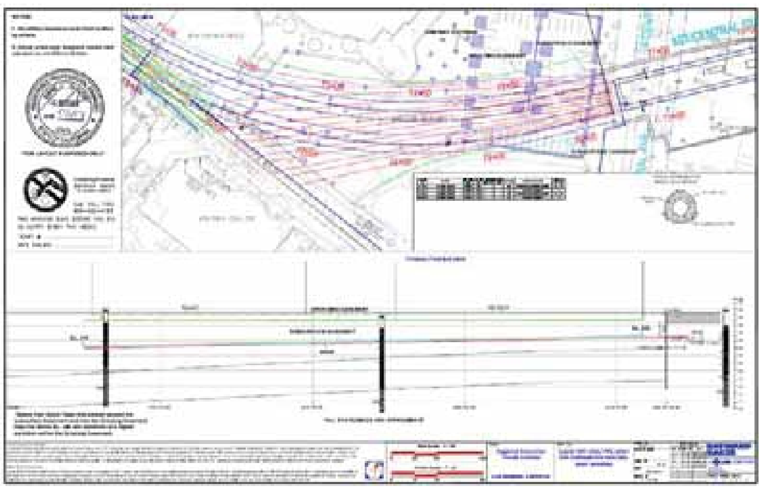
HMG is composed from a mix of water with cement, bentonite, additives, fly ash, lime, and additives, etc. “The principle of grouting is to fill the open voids existing in a rock mass in introducing, by pressure through boreholes, a certain amount of a "liquid" matter, in fact a suspension, that will harden later on” (Lombardi 2001). HMG is widely used for dam cut-off curtains, grout bonding zones of anchors and micropiles, etc.

This presentation will provide a case study of HMG application in rock formations, a curtain grouting projrct in Wolf Creek Dam in Kentucky, USA. The state of art technologies have been applied for this HMG project, including the drilling and grouting equipment, DAQ and control system, and QA/QC.

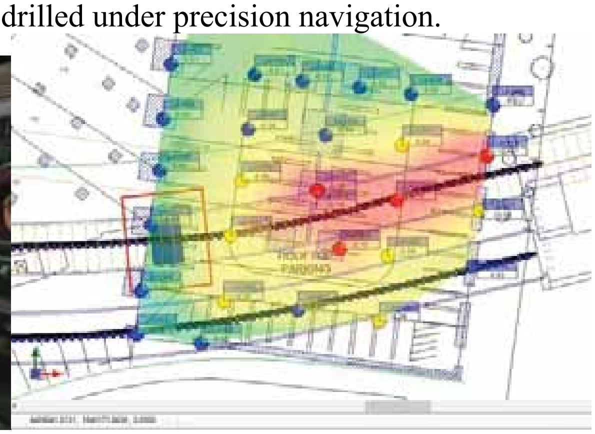
Wolf Creek Dam was built during 1941~1943 and 1946~1952. The construction interrupted during II World War. The dam formed the largest reservoir in eastern US with 7.4 billion m^3 water storage. This dam is listed as the most critical problem dam among the major dams in US. Severe leakage and sinkholes were detected since 1967 due to the erosions in the karstic limestone below the dam. The limestone rocks have been treated repeatedly by HMG since 1943.



Fraction grouting is an application of HMG in soils. Under the pressure, HMG fractured into soil matrix, densify and heave the ground. It is commonly used to reverse total and differential settlement caused by tunneling and soil consolidation, as demonstrated by the compensation grouting project for Los Angeles Regional Connector Project.



13 sleeve port grout pipes, ranging in length from 220 to 430 ft to depths up to 35 ft beneath the overlying structures, were directionally drilled under precision navigation.

The HMG injection was guided by a precision real time settlement monitoring system, including liquid levels, portable and fixed tilt meters, laser total stations, and SAA shape arrays. All compensation grout injections were performed utilizing Hayward Baker's I-Grout data acquisition and control system. There were two grouting phases, pre-conditioning grout prior TBM tunneling, and during TBM passing.

Bio of Speaker

Dr. Shao serves as the chief engineer of Hayward Baker Inc Western Region, in charge of ground improvement design, analysis, quality control, and technology development. His work focused on liquefaction mitigation, soft soil improvement under heavy building structures, excavation support, and dam rehabilitation, by vibro stone columns, soil mixing, jet grouting, micropiles, compaction grouting, fracture grouting and permeation grouting, etc. He joint Hayward Baker, Inc in 1997.

He is a Professional Engineer and Geotechnical Engineer registered in California, North Carolina, Hawaii, and Alberta. He received his PhD degree in 1995 from North Carolina State University. He has published over 50 technical papers in geotechnical engineering.

Deep excavation in Shanghai soft strata and its influences on adjacent buildings and facilities

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Abstract

This presentation briefly introduces the state of art and practice for design, construction and instrumentation of deep excavation in Shanghai soft strata as well as excavation performance and its influence on adjacent buildings and facilities. The rapid urbanization in Shanghai within the past three decades demanded for thousands of deep excavations for metro lines, basements of high-rise buildings, underground parking garages, underground shopping malls and other buried facilities. Due to shortage of land for development, more and more excavations featuring mega-scale, great depth or complex geometry (e.g., pit-in-pit configuration) have to be conducted in the congested urban areas. Thereby, protection of pre-existing structures and facilities and mitigation of excavation-induced adverse effects on urban environment are the first priorities for owners and contractors. Excavation performance is affected not only by soil-water-structure interactions but also by many other factors (e.g., pit size and geometry; supporting system; excavation method; basal treatment scheme; workmanship; adjacent structures and facilities; weather condition). Currently, it is still difficult for the developed methods in literature to give an accurate or a reliable prediction on excavation performance in advance, see Fig. 1. Consequently, there exists a high incidence of excavation accidents or even catastrophic failures.

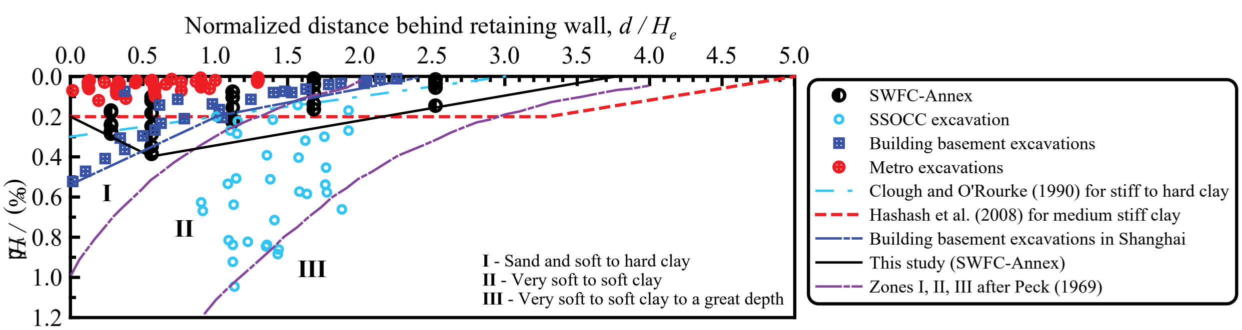

Fig. 1. Comparison of excavation-induced ground settlements in Shanghai with those predicted.

Due to inherent complexity of stress-strain behaviors of soft clays (e.g., small-strain, creep and sensitive structures), current excavation design still relies primarily on the traditional beam-on-elastic-foundation method by inputting empirical subgrade reaction moduli back-calculated from excavation database. Most excavations were constructed by bottom-up (BU) method and those in the congested downtown areas were usually constructed by top-down (TD) method with much stiffer supporting system. Recently, semi-top-down (STD) method, which combines the merits of both BU and TD, has been successfully implemented into several excavations closely surrounded by existing superstructures (Tan et al. 2016). For large-scale excavations of skyscrapers with podiums, they were usually excavated by the central-island (CI) method (Tan and Wang 2013a, b); other large-sized excavations were usually constructed by zoned-excavation method. Because of the soft subsurface conditions, deep excavations were usually retained by multipropped rigid retaining walls (diaphragm wall, continuous bored pile wall and secant pile wall) rather than flexible or anchored retaining walls. Both shallow phreatic level and underlying aquifers demand dewatering and construction of waterproof curtains (mix-in-place or jet-grouting columns) along pit perimeter for performing excavation safely without severe through-wall water/soil leaking or piping/sand-flow hazards. Soil removal inside pit followed either a basin-type or an island-type procedure. To mitigate risk associated with excessive lateral wall displacement or wall kicking failure, basal soils of those excavations bottoming out in soft clayey strata were enhanced by grouting prior to excavation. Because of strong creep behavior of Shanghai soft clay, it is recommended that excavations follow a procedure of quick excavation, prompt propping, timely casting and segmented construction procedure to mitigate potential adverse effect arising from long excavation duration and large wall exposure length (Liu and Hou 1997; Tan et al. 2015).

To safeguard projects and mitigate project risk, performance-based design philosophy has been implemented in local practice since 1990s (Liu and Hou 1997), in which excavations should be closely monitored and both design and construction should be dynamically adjusted according to feedbacks from field instrumentation. The amounts of well-documented field data provide rare opportunity for in-depth investigation on excavation performance and evaluation of its influence on urban environment. In case of similar earth retaining systems, TD excavations featuring much greater system stiffness often did not incur smaller wall displacements than BU excavations featuring much shorter excavation duration; STD excavations exhibited a better performance than both BU and TD ones. Despite of this, TD excavation has much better structural integrity and thus the probability of quick evolution from local failure into global instability would be much lower than that of BU excavation. If an excavation was designed with appropriate parameters [supporting system stiffness, wall penetration ratio and factor of safety against basal heave (FOS)], additional increase of these parameters could hardly further reduce lateral wall displacements and associated ground settlements, see Figs. 2 and 3. In such case, excavation performance was more related to other factors (e.g., excavation duration, wall exposure length, excavation depth, and pit size). Generally, the greater magnitudes these parameters were, the poorer excavation performance was. Pit geometry is another key factor associated with excavation performance. Generally, circular excavations exhibited the best performance while regular rectangular excavations with an aspect ratio (AR) of 1-2 showed the poorest performance; long and narrow subway excavations had immediate performance. For the unique pit-in-pit excavation, it is crucial to control lateral wall displacements of its inner pit. Distinct from regular rectangular excavations exhibiting strong spatial corner stiffening behavior, the mobilization of corner stiffening effect in long and narrow subway excavations is inherently related to wall exposure length along longitudinal pit side; short wall exposure length will suppress mobilization of pit corner stiffening effect. During excavation, basin-type soil removal procedure can restrain lateral wall displacements while island-type soil removal procedure can constrain basal heave. If an excavation was terminated in soft clayey strata, basal treatment by grouting was essential; otherwise, excessive wall deflections or even wall kicking failure could take place. However, if excavations were bottomed out in stiff clayey strata, they could be done without basal treatment, which would not undergo greater displacement than those with basal treatment. Although receiving much less attention than both wall and ground displacements, basal heave in soft strata is remarkable and should be paid with serious attention, which can be up to $0.9\,H_e$ (H_e denotes final excavation depth). Pronounced basal heave accompanied by significant vertical displacements of retaining wall and interior columns will impair axial capacity of braced struts and then threaten global stability of earth supporting system. Apart from excavation, construction of retaining wall prior to excavation can lead to dramatic ground settlements as well (Tan and Lu 2017), which can be up to 0.15%D and extend 2.0D behind wall (D denotes wall height), see Fig. 4.

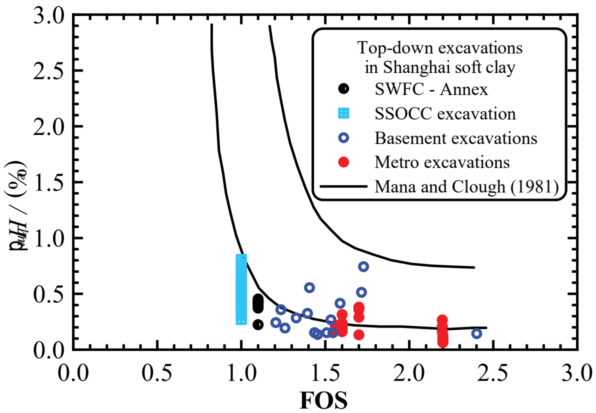

Fig. 2. Wall displacement vs. FOS.

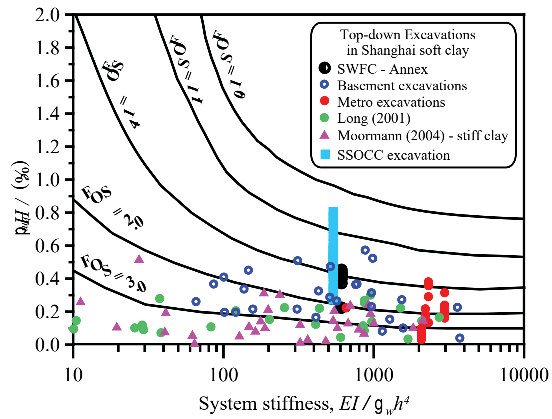

Fig. 3. Wall displacement vs. system stiffness

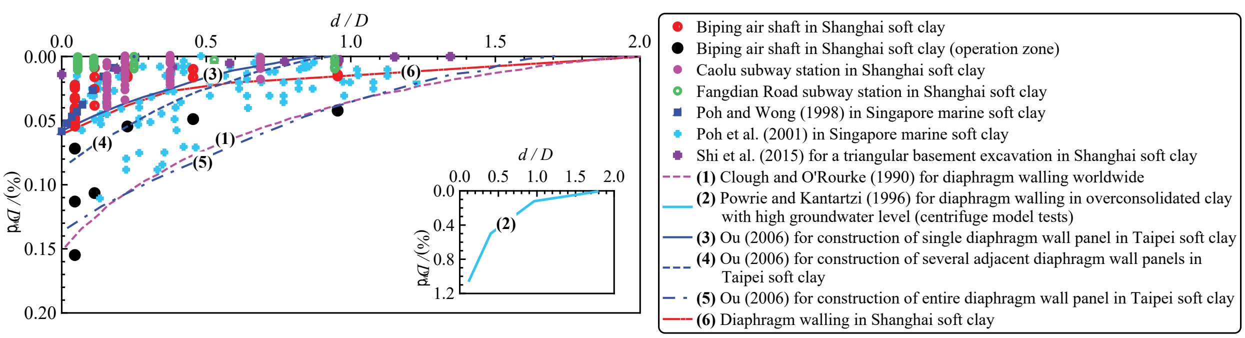

Fig. 4. Diaphragm walling-induced ground settlement in soft clayey strata.

Intolerable ground displacements caused by excavation will cause damages to structures and facilities in the proximity. Adjacent excavation-induced building settlements are mainly governed by location of building relative to pit, ground settlement influence zone, building dimension in plan and foundation type, among which foundation type is one of the dominant factors. In general, raft foundation, raft slab atop dense short piles/columns and piled raft foundations are stronger than strip footing, strip footing atop long piles, and shallow foundations, respectively, in resisting building settlements. Different from the assumptions in literature, development of building settlements on either shallow or deep foundations is not always concurrent with development of ground settlements during excavation. Development of building settlements is closely related to the extension of the ground displacement zone underneath. Before cracking damages the effective wall stiffness, building settlement is much smaller than underlying ground settlement; however, once the effective wall stiffness is impaired by cracking, building settlement conforms to ground settlement trough quickly. For buildings on short piled foundations, extending pile toes below excavation base can result in significant reduction in excavation-induced building settlement. Another cost-effective alternative is to control H_m (the depth where the maximum lateral wall displacement takes place) close to ground level by adjusting strut numbers and locations without sacrifice of excavation performance (Tan et al. 2016). Regarding shallowly buried pipelines adjacent to excavations, their displacements are predominantly governed by the pipeline locations relative to pits. Contrary to the theoretical assumptions in literature, adjacent excavation-caused pipeline displacements are much less affected by pipeline flexural rigidity or soil bedding stiffness for either flexible or rigid pipelines; their magnitudes can be estimated with derived empirical functions in terms of pit geometry, excavation depth and location of pipeline relative to pit (Tan and Lu 2018).

In summary, performance of deep excavations in Shanghai soft strata and its influence on adjacent buildings and facilities are inherently complex, which are affected by many factors involved in both design and construction. There exists no universal law for accurate prediction on excavation performance. To better understand excavation behaviors and mitigate its adverse influence on urban environment, it is essential to closely observe excavation performance in the field and interpret it correctly. As pointed out by Terzaghi (1948), the more plain facts we can accumulate, the very core of substance can be disclosed more clearly and then much more satisfactory excavation works can be achieved in the future. From the perspective of this, the findings and lessons learned from excavations in Shanghai are practically useful addition to the literature for upgrading current state of art and practice in deep excavation.

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Bio of Speaker

Dr. Tan holds a B.Eng. in Building Engineering from Tongji University (1999), a M.Eng. in Geotechnical Engineering from Tongji University (2002), and a Ph.D. in Civil Engineering from the University of Massachusetts (2005). Subsequent to his doctoral research he joined Terracon Consultants, Inc. in Savannah, Georgia, USA as Staff Geotechnical Engineer and later was promoted to Project Engineer. In June, 2009, Dr. Tan joined the Department of Geotechnical Engineering at Tongji University as Lecturer. He was promoted to Associate Professor in December, 2011 and Full Professor in December, 2016. Dr. Tan is the recipient of the prestigious Outstanding Journal Paper Award of 2014 from ASCE Forensic Engineering Division for his integrated research on spatial corner stiffening behaviors of subway excavations in Shanghai soft clay. Additionally, he was awarded the 2010, 2013, and 2015 Research Grant Awards by the International Press-In Association (IPA) and his publications on ASCE Journal of performance of Constructed Facilities were twice nominated for Outstanding Journal Paper Award (2010, 2012). His research has been supported by both state agencies and local industrial companies. Dr. Tan has developed close collaborations with both industry and academia and has been deeply involved in engineering practice. Dr. Tan's areas of specializations include deep excavation and tunnelling, forensic investigation and foundation engineering. He has already published over 40 technical papers as the first or corresponding authors on these topics in leading professional journals, most of which were published by the American Society of Civil Engineers (ASCE). Five of the ASCE journal papers were Top 1% ESI highly cited papers and two ASCE companion papers were Top 0.1% ESI hot papers. Dr. Tan is an active member in several professional societies including ASCE, International Pressure-In Association (IPA), and Associated research Centers for the Urban Underground Space (ACUUS).

Vacuum preloading technique for dredge clay slurry improvement: Applications and innovations

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Abstract

This presentation introduces the recent research and practice of vacuum preloading technique for dredge clay slurry improvement, including technical problems in the vacuum preloading for the dredge clay, air booster-vauum preloading technique and floc-vacuum preloading technique.

Because the dredged soil consists of fine particles, when the conventional vacuum preloading technique is employed for the treatment of the dredged clay, the fine particles will move with the outflow of water. They may block the filtration pore of the PVDs. Some of them may even pass through the filter and then infiltrate into the core of PVDs, making the block of drainage channel. In addition, as time goes by, soil columns may be formulated surrounding the PVDs. They also clog the movement of free water into the PVDs. Consequently, the discharge capacity of the PVDs may be significantly reduced. In turn, it will causes insufficient consolidation in deep soil layer and excessive settlement after construction.

Air booster vacuum preloading technique adopts both a vacuum and an air booster system. The air mass around the Booster tube will be generated by the booster system to increase the pressure difference between the PVD and Booster tube to accelerate the soil dewatering and consolidation. The testing data shows that better consolidation results are achieved using the improved vacuum preloading method (Wang et al, 2016). But the booster tubes could be inserted into a depth of 5 m only with manpower, which serious limits the use of this technique in the treatment of deep soft soil. In addition, the booster tube has no drainage function, which means that additional PVDs will be installed next to booster tubes to reinforce the part of the soil. To adapt the air booster vacuum preloading technique to the improvement of deep clay layers, the booster PVD is proposed for the replacement of conventional booster tube so as to overcome its small embedment depth. The booster PVD shows no difference from the ordinary PVD except that it plays the role of booster tube that provides the inflow channel of the compressed air when the booster pump is activated. To examine the performance of the improved air booster vacuum preloading technique, in-situ field tests are conducted at a land reclamation site where the total thickness of the soft soil layers was more than 20 m. The results show that the improved air booster vacuum preloading technique is competent for improving the deep marine clay layers as deep as 20 m.(Cai et al)

Floc-vacuum preloading technique is achieved by adding some flocculants (floc) to the dredged fills while maintaining a certain level of vacuum pressure through prefabricated vertical drains (PVDs). The floc agent would significantly mitigate the risk of clogging around PVDs and enhance the soil permeability, thereby improving the efficiency of consolidation. (Cai at al, 2015). For example, by adding hydrated lime to dredged clay slurry, two reactions will take place. The first one is the cation exchange reaction & flocculation. In this process, tiny clay particles will

aggregate into larger-sized particles. So, the void ratio and permeability are increased. The second one is the pozzolanic reaction & lime carbonation. In this process, calcium carbonate will be generated. It can enhance the cementation and strength of the soil. By these means, the efficiency of vacuum preloading technique can be enhanced. Lime modification optimum (LMO) is also determined using the vacuum preloading method firstly, and a comparison test was then conducted to verify the effectiveness of the this method. It was found that, compared to the conventional vacuum preloading method, the proposed method significantly increased the vane shear strength of all the soil layers, especially the deep soil layers, and afforded a higher consolidation rate. (Wang at al., 2017)

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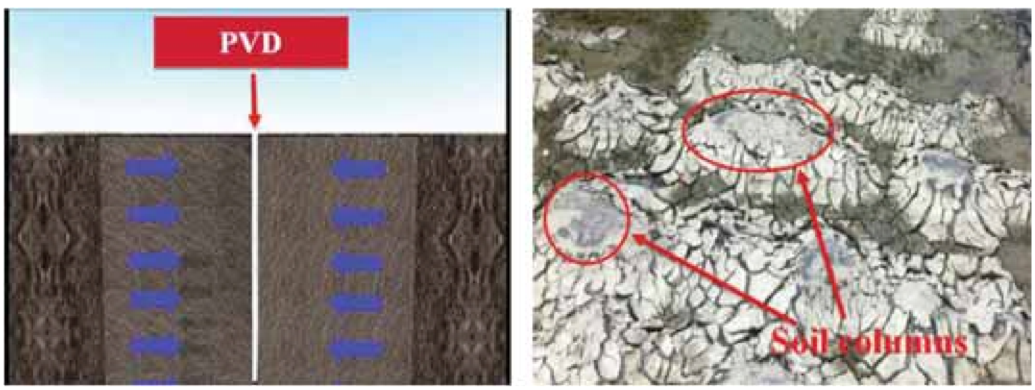
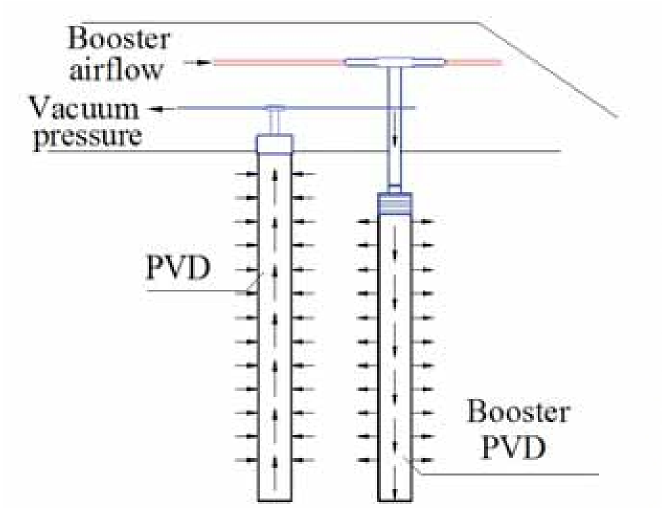
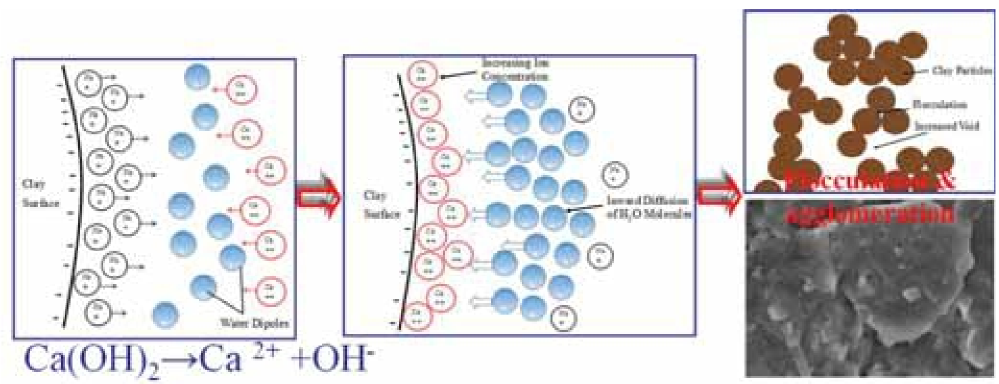


movement of the soil particles and clogging soil column around the PVD



The improved air booster vacuum preloading technique



Cation exchange reaction

Bio of Speaker

Dr. Yuanqiang Cai is a professor of Geotechnical Engineering, Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, China. He received his BS, MS, and Ph.D. degrees from Zhejiang University in 1987, 1990, and 1998, respectively. His research interests include soil dynamics, ground treatment, and foundation engineering. He serves as an editorial board member for the Chinese Journal of Geotechnical Engineering, the Rock and Soil Mechanics journal, the Journal of Vibration Engineering, and the Journal of Zhejiang University Science (A). He is a member of ISSMGE-TC217 Land Reclamation Technical Committee, a member of the American Society of Civil Engineers, an associate director of the Rock Mechanics and Engineering Council of China, Environmental and Geotechnical Division, an associate director of the Chinese Society of Theoretical and Applied Mechanics, Geotechnical Mechanics Division, and the managing director of the China Civil Engineering Society, Chinese Institution of Soil Mechanics and Geotechnical Engineering. Prof. Cai has published a monograph "Solutions for Biot's Poroelastic Theory in Key Engineering Fields" and more than 70 SCI-indexed research papers in peer-reviewed journals. Prof. Cai is the Senior Expert of Zhejiang Province, People's Government of Zhejiang Province, China, since 2015 and the Leading Researcher of Millions of Leading Engineering Talents, the Organization Department of the Communist Party of China Central Committee since 2014.

Dredged clay improvement by modified vacuum preloading technique

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Abstract

With the proposal of strategic planning of the "Ocean Power of China", "The Belt and Road" and Yangtze River economic belt, there has been a heated wave of reclamation in the coastal area of China. It brings unprecedented opportunities and challenges for soft soil foundation reinforcement technology development (Zheng et al. 2016). However, the newly reinforced land is mainly formed by dredging and filling the dredged silt, which shows bad engineering property: high water content (100%-300%), great void ratio, large compressibility, low permeability and small shear strength (Lei et al. 2018). Research shows that foundation treatment with the vacuum preloading technique has been extensively used in coastal belts of China. However, as the reclamation area continues to increase, the conventional vacuum preloading technique (CVP) faces many new challenges such as clogging of prefabricate vertical drains (PVDs), secondary treatment requirement and high electricity consumption (Lei et al. 2017 a). Therefore, many scholars and engineers spare no effort to seek for new method to solve the unpleasant issues.

Based it on, this presentation introduces two kinds of modified vacuum preloading techniques to evaluate the reinforcement effect in terms of dredged clay, such as improved air-booster vacuum preloading technique (AVP) and improved synchronous and alternate vacuum preloading method (SAP).

AVP adopted both a vacuum preloading system and air- pressurizing system. In the vacuum system, the hand type connect each prefabricate vertical drain (PVD) directly to a horizontal vacuum pipe. In the air - pressurizing system, the air is injected into the soil, forming the lateral pressure, to compact the soil. The key of this method is to take the auxiliary means of air injection during the process of vacuum preloading. Field pilot tests using both AVP and CVP were carried out at same site. Based on monitoring data, settlement, pore water pressure and hydraulic conductivity are studied to demonstrate that the air- pressurizing system can boost the consolidation process. In addition, in terms of the effect of vacuum preloading treatment, both soil sensitivity and the foundation bearing capacity determined by the vane shear strength are discussed.The testing data showed that better consolidation results were achieved using the AVP.

SAP is an improved technique with alternate vacuum working towards orthogonal directions and deep-shallow synchronous treatment. Based on the nature of PVDs clogging, oriented migration of fine particles which accumulated a dense, rare permeable mud layer cling on the surface of PVD, this new method was proposed (Lei et al. 2017b). In this technique, PVD was crisscrossed located and vacuum pressure exerted in alternate manner, which disturbing the migration of fine particle movement. Furthermore, to achieve the one time treatment, PVD was penetrated with different depths. Cross PVD was deeply located, then lengthways PVD was shallow located, vice versa. Laboratory model tests were conducted to investigated the proposed both improved techniques modified with conventional vacuum preloading method. Test result

demonstrates that the ultimate water discharge of soil treated by SAP is greater than that treated by CVP, which can improve more than 30%. With respect to the consolidation behavior of dredged clay treated by SAP, the average degree of consolidation and the shear strength were outstandingly improved.

The introduction of two types of modified vacuum preloading technique is aimed to provide the new ideas for CVP and promote the development of new technology.

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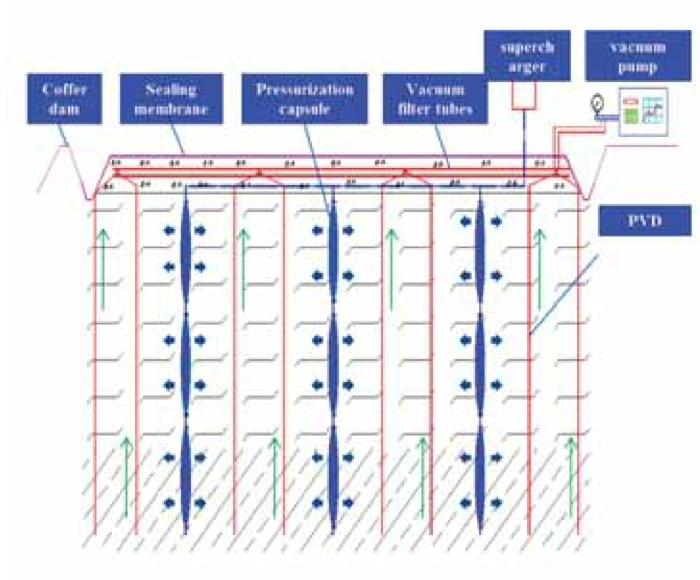
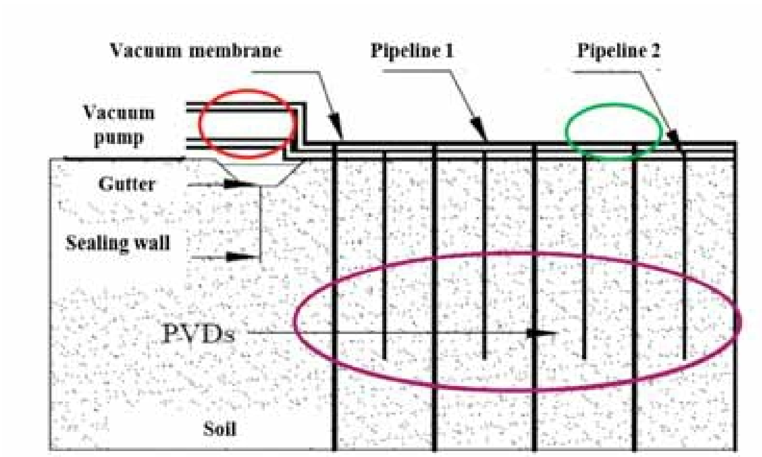
Dredged clays



Improved air-booster vacuum preloading



Improved synchronous *and* alternate vacuum preloading method

Bio of Speaker

Dr. Huayang Lei is a professor in Geotechnical Engineering at Department of Civil Engineering of Tianjin University. She serves as the director of Underground Engineering Laboratory, Key Laboratory of Coast Civil Structure Safety of Education Ministry. Her research has focused on soft soil engineering properties, soft ground improvement and underground engineering. She has published more than 120 technical papers in journals and conference proceedings.

Dr. Lei is the vice-director of Youth Working Committee and Soil Mechanics Teaching Specialized Committee and also the vice secretary-general of Soft Soil Engineering Specialized Committee of Chinese Institution of Soil Mechanics and Geotechnical Engineering, China Civil Engineering Society.

Electro-osmosis theory, EKG and challenges in large scale electro-osmotic consolidation

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Abstract

Dredging and sludge treatment attract more and more attentions with the growing concern of environmental issues. There is recently a lot of dredging work going on for cleaning of rivers, lakes, channels, canals, reservoirs, etc. in China. Dredged sludge is hydraulically filled into an area for flocculation and sedimentation; then dewatering of sludge after sedimentation is usually carried out by filter press. For dredging project, there is normally huge volume of sludge to be dewatered before disposal. Besides dredging, hydraulically filled area also comes from land reclamation. Land reclamation provides a solution for growing land demand, therefore, it plays a significant role in many countries, such as Netherlands, Japan, Singapore, Korea and China (Hoeksema 2007; Yang 2003; Zhuang et al. 2013; Zhuang et al. 2014).

Dewatering of sludge is difficult due to its high water content and low hydraulic permeability. For these fine-grained materials with high water content and low hydraulic permeability, electro-osmosis can be an alternative method of dewatering. Phenomenon of electro-osmosis was discovered by Reuss in 1809. He found that DC field can migrate moisture from anode to cathode, so that water can be removed from the sludge through the discharging channel around cathode. Electro-osmosis is governed by electric field other than hydraulic gradient. Because electro-osmotic permeability is effectively independent of grain size, electro-osmosis can result in flow rates 100 to 10000 times greater than hydraulic flow in fine-grained materials (Jones et al. 2008).

Electro-Kinetic Geosynthetics (EKG) are a series of novel geosynthetics that provide corrosion proof electrode for electro-osmotic dewatering. Concept of EKG was presented by Jones et al. in 1996 (Nettleton et al. 1998); and ability of mass production of EKG was achieved recently in China (Zhuang et al. 2012, see Figure 1-2), due to the advance of electrical conductive polymer. Several field trials have been carried out and the promising effects inspire enthusiasm for further research on EKG and electro-osmotic consolidation (Zhuang 2015b, see Figure 3).

Challenges of electro-osmotic consolidation in large scale application are as follows

1. Electro-osmosis theory

Classical theory of electro-osmotic consolidation was presented by Esrig in 1968. However, it cannot predict variation of electric current and energy consumption, which are important for selection of power source and cable for design of electro-osmotic consolidation. Energy level gradient theory is presented as a fundamental theory to propose design method for electro-osmotic dewatering and consolidation.

2. DC power source

Energy consumption of electro-osmotic consolidation is within 10kwh/m^3, which is similar to that of vacuum consolidation. However, electro-osmotic consolidation is much quicker than vacuum consolidation and this indicates that energy input should be much quicker. Therefore, we can expect that electric power required for electro-osmotic consolidation is much higher. As a comparison, for hydraulic-filled sludge of 5m deep, electric power required for vacuum

consolidation is around 10 watt/m^2 only, while 100 watt/m^2 is required for electro-osmotic consolidation.

The solution is to carry out roll polling electro-osmosis scheme by optimal utilization of electro-osmosis intermittent time. During electro-osmosis, dewatering will continue for a certain time after electric current stops. Therefore, a rolling scheme can be designed to carry out electro-osmotic dewatering section by section. High power demand appears only at the beginning of electro-osmosis, when the current decreased following exponential function, more area sections can be connected in. To carry out the rolling scheme, automated DC power source is created. The novel designed DC power source (see Figure 4) has a roll polling program embedded, which can automatically connect to different area sections according to the monitored current.

Figure 1 Photo of E-board

Figure 2 Photo of E-tube

Figure 3 Field trial of soft ground improvement by electro-osmotic consolidation

Figure 4 DC power source

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Bio of Speaker

Dr. Yan-feng Zhuang is currently an associate Professor at Wuhan University. He has broad interest and overlapping education and work experience including geotechnical engineering, water treatment and clay minerals. Dr. Zhuang has been working on electro-kinetics of soil for about 20 years. He received his Ph.D. in 2005 for his work on Electro-Kinetic Geosynthetics (EKG). He won the IGS Student Award in 2006 in Yokohama for his Ph.D. work; and he won the Young IGS Member Achievement Award in 2014 in Berlin for his work on EKG and electro-osmosis theory. He provides consultancy for companies that are manufacturing EKG, aiming at deep soft ground improvement or sludge dewatering.

Scale up and field trials on bio-based ground improvement methods

Leon van Paassen [1]

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Abstract

The last decades a significant amount of research effort has been spend investigating the potential of bio-based ground improvement methods to improve sustainability and reduce environmental impact of geotechnical engineering practice. There are many biological processes, which alter the hydrological and mechanical properties of soil: biophysical processes such as burrowing animals or growing plant roots compact, loosen or segregate soils after deposition. Biochemical processes may leach, oxidize, hydrolyse or precipitate minerals, changing the pore structure and composition of the soils. One of the main processes under investigation has been the microbially or enzymatically induced carbonate precipitation through hydrolysis of urea. Injecting ureolytic micro-organisms plant extracted urease enzymes or stimulating ureolytic micro-organisms in the ground and supplying them with a solution of urea and calcium chloride, will result in the hydrolysis of urea and precipitation of calcium carbonate. While the calcium carbonate minerals reduce porosity and permeability or may increase strength and stiffness, the remaining ammonium chloride needs to be extracted and disposed. Theoretical models have been developed, with various level of complexity, which allow to predict the spatial and time-dependent distribution of the reaction products. Empirical correlations have been established, relating the amount of calcium carbonate to geotechnical properties, such as strength, stiffness, porosity and permeability. These theoretical models and empirical correlations can be used to design treatment procedures, in which process outcomes (distribution of calcium carbonate and the resulting ground properties such as strength or stiffness, but also costs and environmental impacts) can be predicted as a function of the process variables (urease activity, substrate concentration, amount of injections, injection strategy, pumping rate and time) and initial ground conditions (soil type, grain size distribution, grain texture, packing density, initial porosity, permeability, etc.).

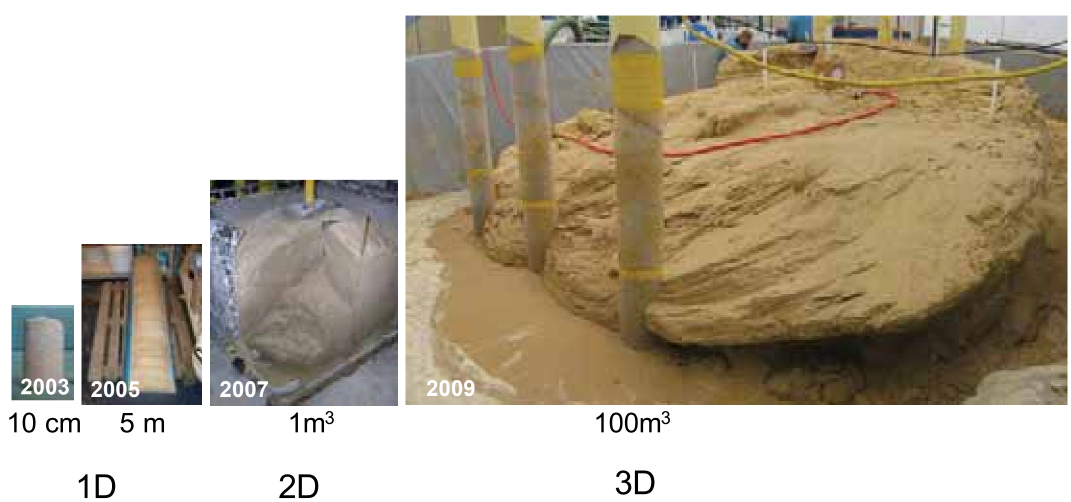

Figure 1 Scale up of Microbially Induced Carbonate Precipitation (MICP) by urea hydrolysis

Although the technical feasibility of this process has been demonstrated and several field trials have been performed, the amount of field trials and full scale commercial applications is still limited. One of the reasons for the limited applicability is the costs to implement the process at a larger scale. Based on the first field trials the expected costs are estimated to range from 150 to 400 USD /m^3 of treated soil. Costs were equally divided over the required substrates, the cultivation of bacteria, the extraction and disposal of the residual ammonium chloride and mobilization of equipment. Recent optimization efforts aim to reduce costs for cultivation of ureolytic bacteria, try to stimulate indigenous ureolytic bacteria in situ or try to find and optimize extraction from alternative plant-based sources of urease, aim to reduce the required amount of substrates to obtain a target strength by improving the cementation efficiency or find solutions to deal with the residual ammonium chloride.

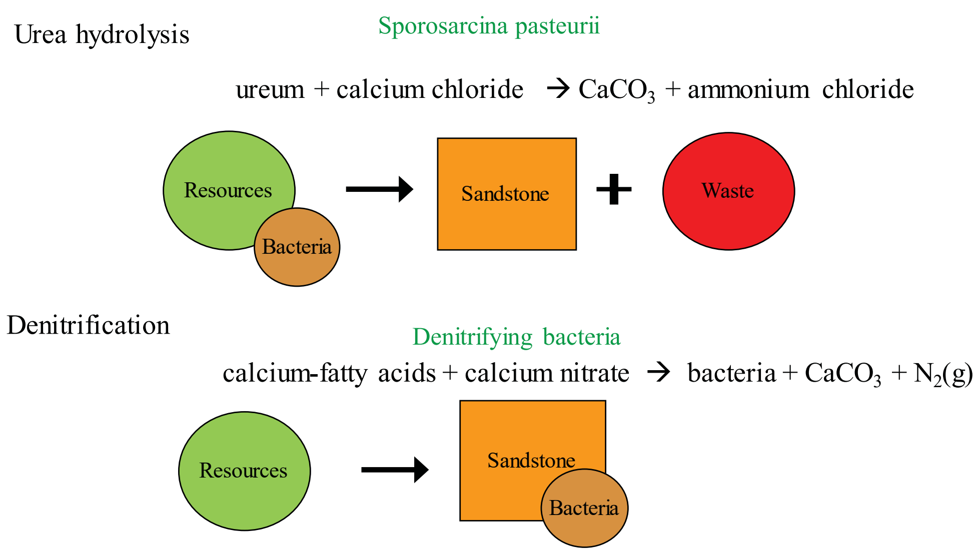

Figure 2 The main two biological processes leading to precipitation of calcium carbonate are urea hydrolysis and denitrification.

Alternative processes resulting in precipitation of calcium carbonate have been explored, in particular MICP by denitrification. In this process, a solution containing nitrate, calcium and acetate (or another soluble organic carbon source) is injected in the ground. The organic substrates are oxidized by indigenous denitrifying bacteria using nitrate as oxidizing agent. This catabolic reaction allows the bacteria to grow and produce biomass and results in the production of nitrogen gas. While the precipitation increases strength, stiffness and dilatancy, the biomass and nitrogen gas fill up the pores space and reduce permeability. The nitrogen gas also increases the compressibility of the pore fluid, dampens pore pressure build up during cyclic loading, which may be used to mitigate earthquake induced liquefaction. The denitrification process appeared to be significantly slower than the hydrolysis of urea hydrolysis, but the lack of byproducts, the ability to use indigenous bacteria and the potential to use industrial waste streams rich in organic matter and nitrate as substrates are considered significant advantages. Desaturation through nitrogen gas production may be even more sustainable as the amount of required substrates to sufficiently desaturate the soil is very small compared to the requirement for cementation. However, the durability and distribution of the gas phase still needs to be investigated and the technical feasibility of the process has never been demonstrated at a large scale. Therefor significant efforts of both academia and industry are still required to solve the remaining challenges and scale up these processes towards full scale applications in geotechnical and geo-environmental engineering.

Bio of Speaker

Leon van Paassen is Associate Professor at Arizona State University (ASU) and Senior Investigator at the NSF Engineering Research Centre for Bio-mediated and Bio-inspired Geotechnics (CBBG). He received an MSc in Applied Earth Sciences in 2002 from Delft University of Technology with a specialisation in Engineering Geology. During and after his graduation he worked several years as a geotechnical engineering consultant at IFCO Foundation Expertise and at research institute Deltares. In 2009 he obtained his PhD from the Department of Biotechnology of Delft University of Technology. His PhD research on 'Biogrout, Microbially induced carbonate precipitation as ground improvement method' resulted in several publications, patents. For which he has received several national and international awards. His current research integrates the fields of environmental biotechnology and geotechnical engineering. He investigates how natural or human-induced biochemical processes affect soil behaviour and aims to develop sustainable solutions, which improve efficient use of resources and energy and reduce the environmental impact of civil and mining engineering industry.

Bio-geotechnologies for soil improvement: Recent advances

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Abstract

Microorganisms in soil environments and their activities can alter the physical and mechanical behavior of soils. The microbial processes can be controlled and used for soil improvement and other geotechnical applications. In this extended abstract, we introduce our recent research advances in bio-geotechnologies in three aspects: a new technique that allow the microbial treatment to be used in silty sand; an understanding of the combined effects of microbial treatment and soil density on the mechanical behavior of sand; and microbial treatment based on the denitrification process.

Microbially induced carbonate precipitation (MICP) process can produce cementation effect in soils and greatly enhance the strength and stiffness of soils. This process can be employed as a soil improvement method. However, in previous studies, the MICP method was only suitable for the treatment of sand with limited amount of fine soil particles. One of the major reasons is that, bacteria have strong tendency to adhere to soil particle surfaces, which limits the range and the depth of the treatment in soil grounds (Harkes et al. 2010). To overcome this limitation, an alternative approach can be adopted that uses crude enzyme urease for the soil treatment instead of using live bacteria directly. Crude urease can be obtained through cell lysis. The cell lysis is a process in which a cell is broken down or destroyed as a result of some external force or conditions, such as chemical reactions, osmotic pressure, electrolysis, ultrasonic waves or mechanical forces. It was found in the experimental results that crude urease obtained though the ultrasonics was also capable of hydrolyzing urea and being used in the MICP soil treatment. Besides, silty sand treated by crude urease had more uniformly-distributed calcium carbonate as compared to the same soil treated by live bacteria. In the triaxial consolidated drained tests, silty sand treated by crude urease showed more dilative behavior in the stress-strain curves and volume change curves, as can be seen in Fig. 1.

There are a large number of studies on the mechanical behaviour of MICP-treated sand. However, we are still far from a full understanding of the control factors that allow us to make a reliable design and prediction. As for sands, their shear strength and other mechanical behavior are strongly affected by relative density. So the combined effects of MICP treatment and relative density should be understood. Triaxial consolidated drained and K0 consolidation tests were carried out on sands with different relative densities and treatment levels. In the triaxial tests, plots of peak deviator stress versus relative density for sands with different treatment passes are presented in Fig. 2. In these experiments, 1-pass treatment was equivalent to around 1 pore-volume treatment liquid with 0.5 mol/L urea-calcium chloride concentration. It can be clearly seen that, in the tested conditions, slight MICP treatment can greatly enhance the shear strength of sand, and the bio-cementation effect is more effective than the densification effect. Such results can provide theoretical basis for future engineering practices.

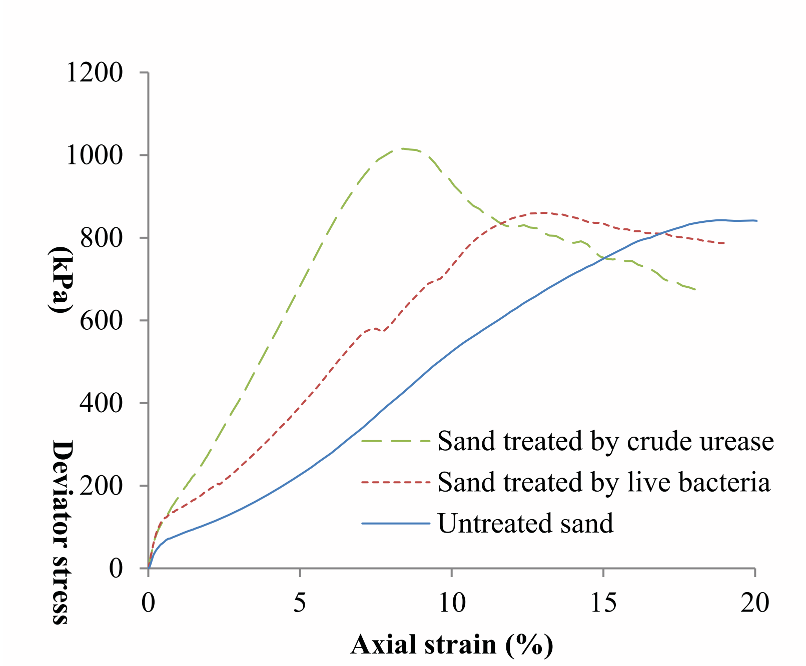
Microbial ureolysis process was adopted in most the studies regarding bio-geotechnologies. However, many other microbial processes can also potentially be used to solve geotechnical problems. Microbial denitrification process is a reduction reaction from nitrate to nitrogen mediated by denitrifying bacteria, as,

$$5C_2H_5OH+12KNO_3 \rightarrow 6N_2\uparrow+10KHCO_3+9H_2O+2KOH \qquad (1).$$

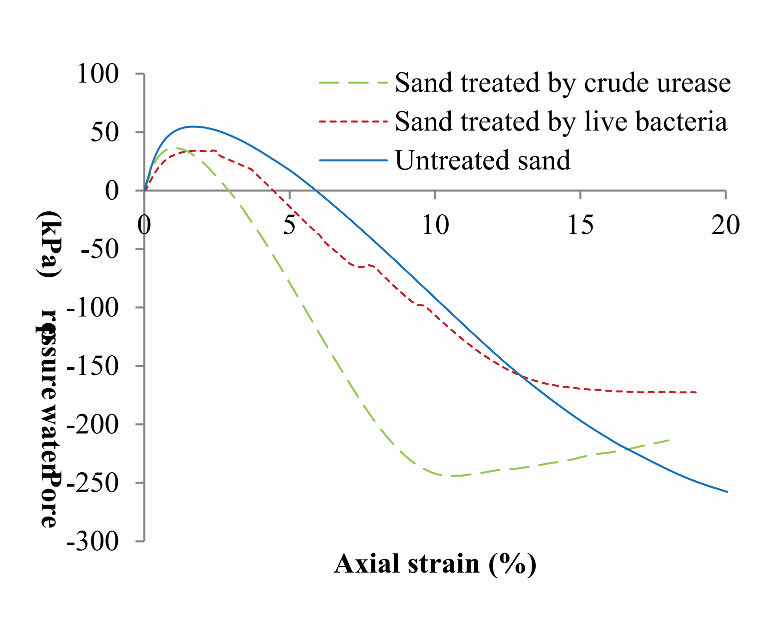
In this reaction, nitrogen gas can be produced in soil and the degree of saturation of soil can be reduced. It has been proven in our experimental studies that the microbial denitrification process can be used to desaturate liquefiable ground for the mitigation or prevention of earthquake liquefaction (He et al. 2013; He and Chu 2014). Furthermore, this microbial process can also bring bio-cementation effect in soil. Bicarbonate/carbonate is produced in the reaction process, as can be seen in Eqn. (1). If aqueous calcium is present in the system, calcium carbonate can be precipitated and serve as a binding agent in soils, as,

$$Ca^{2+}+CO_3^{2-} \rightarrow CaCO_3\downarrow \qquad (2).$$

Therefore, the denitrification process can bring both cementation and desaturation effects in the soil treatment and is suitable for the improvement of liquefiable grounds. In addition, the denitrification process generates less by-products compared with the ureolysis process and causes less disturbance to soil environments.



(a) Stress-strain curves



(b) Volume change curves

Figure 1. Triaxial consolidated drained test results on sand treated by crude urease or live bacteria, and untreated sand

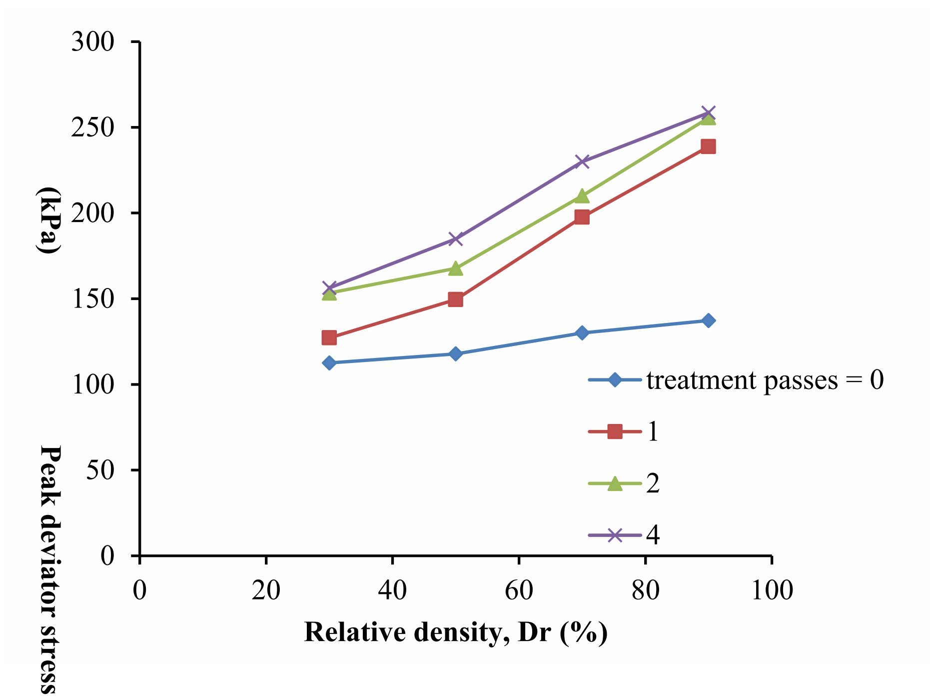


Figure 2. Peak deviator stresses in triaxial tests on sands with various relative densities and treatment passes

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Bio of Speaker

Dr. Jia He is an associate professor at the Geotechnical Research Institute, Hohai University, China. He obtained his PhD in 2013 and worked as a research fellow from 2013 to 2015 in Nanyang Technological University, Singapore. His PhD thesis is Mitigation of soil liquefaction using microbial methods. His research interests include microbial methods in geotechnical engineering, ground improvement, and land reclamation. He published over 30 technical papers in journals and conferences. He is the Principal Investigator for several funded research projects.

The investigation route and project advisement about soft soil improvement

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Abstract

This site investigation and project advisement is aimed to introduce the application of the High-Vacuum Dewatering and Dynamic Compaction Method in the aspect of soft soil improvement based on a project under construction, as well as discuss the efficiency and effectiveness of this method based on completed projects.

The destination of this site investigation is Hangzhou Bay Development Park Industrial Upgrading Area, Zongyi Road Construction Project. The project is in the Hangzhou Bay Development Park, Shangyu City. The distance from the headquarter of Shanghai Geoharbour Group to the Hangzhou Bay Development Park is about 180km, which will take about 2h20m. The site investigation route is shown in figure 1.

The *Zongyi Road Project* possesses about 28,000 m^2. The ground surface of the site is hydraulic silt with slight clay. The ground improvement work adopts the Vacuum Dewatering and Dynamic Compaction Method. Until now the vacuum system is under construction. It is anticipated that until 27th May, the first pass of vacuum drainage will be finished and the first pass of dynamic compaction will be under construction.

The nearby completed projects are about 30 municipal road projects in Shangyu Industrial park, with total area of about 2,200,000 m^2. All of these adopted the Vacuum Dewatering and Dynamic Compaction Method for ground improvement. Some of these roads have been come into service for approximately 10 years and are in good condition. Based on these projects, the technological process, technology principle, construction efficiency and ground improvement effectiveness of the Vacuum Dewatering and Dynamic Compaction Method will be discussed.

Figure 1: Site investigation route

Bio of Speaker

Dr. Xiaoming Lou is the Chief Engineer and the head of the Research and Design Department at Shanghai Geoharbour Group in China. He received his BS degree Department of Civil Engineering from Zhejiang University in 1987 and his MS and Ph.D. degrees from Department of Geotechnical Engineering at Tongji University in 1990 and 2002, respectively. He was a faculty member in Department of Geotechnical Engineering at Tongji University. His expertise is in ground improvement for soft soils.

Soft Soil Stabilization Using Various Admixtures

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Abstract
The paper presents the physical and engineering properties of highly organic soil treated with various types of stabilizer. Quick Lime (QL), Fly Ash (FA), and Ordinary Portland Cement (OPC) were used as stabilizers. The amounts of QL, FA, and OPC added with the soil samples is in the range of 2-8%, 5-20%, and 5-20%, respectively. Various physical or index and engineering tests have been conducted to characterize the highly organic soil samples. Unconfined Compressive Strength (UCS) tests were conducted on original and treated soil samples cured for 7, 14, and 28 days. The results show that the UCS value increases with the increase of all stabilizer used and with curing period. The UCS tests were also conducted on the soil samples with the combination of QL and FA to study the combine effects of the stabilizers. The present study established different correlations between physical and engineering properties of original soil as shown in Fig. 1 and UCS results on treated soil samples with different types of stabilizers as shown in Fig. 2. Geotechnical engineers can refer to these correlations to determine the bearing capacity of treated soil. Also to study the effect of alkali on highly organic soil stabilized with OPC, FA, QL and different chemicals e.g., accelerator (a combination of 2.0% sodium sulfate, 0.5% sodium chloride and 0.1% triethanolamine); 2.6% aluminum sulfate; and 2.6% calcium sulfate. The results show that UCS value increases with curing periods and treated soil samples show better results than untreated soil for both OPC and FA stabilized soil samples. The highest UCS value was found on treated stabilized soil where calcium sulfate and OPC were used as stabilizers. In addition, Scanning Electron Microscope (SEM), studies as shown in Fig. 3, were conducted on original and treated soil samples to investigate the microstructure of the samples.

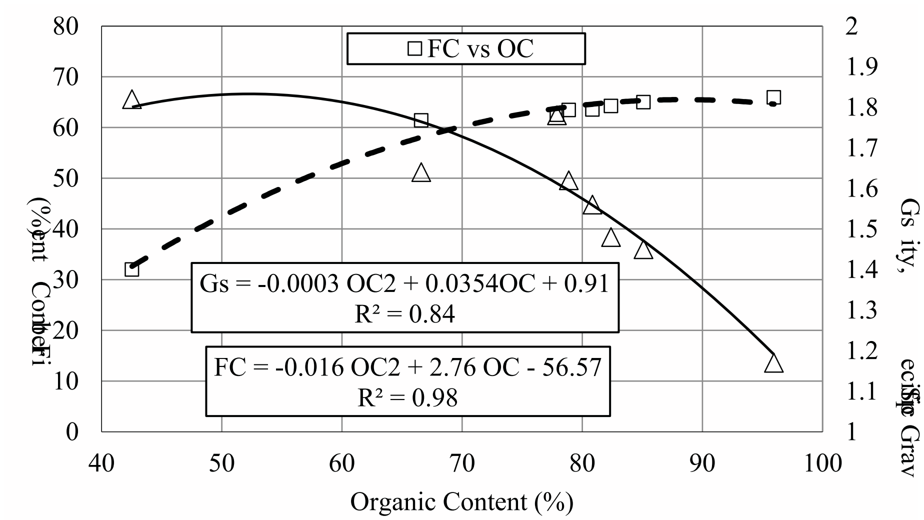


Fig. 1. Correlation between FC, G_s and OC of the soil

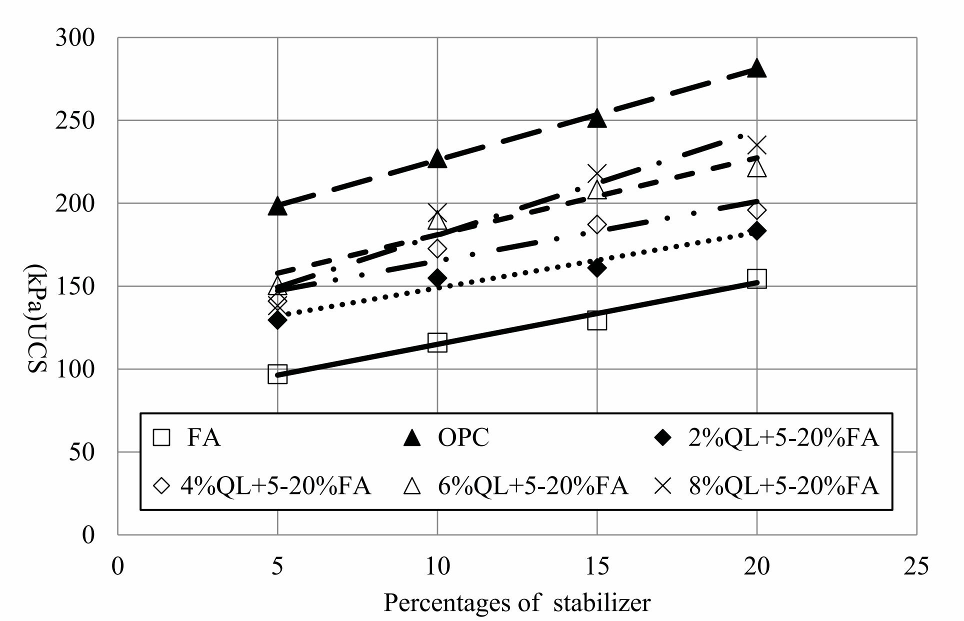
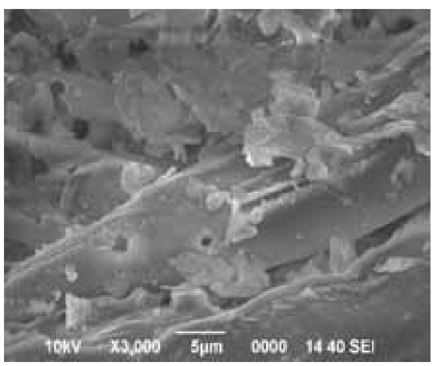
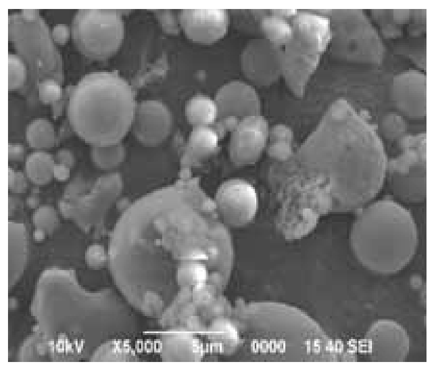
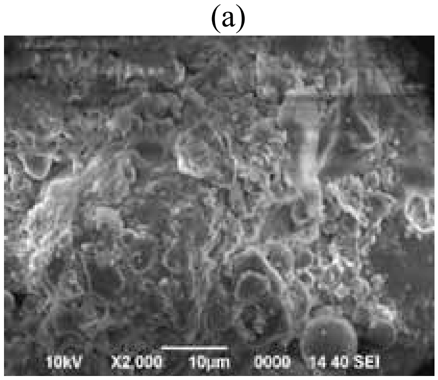
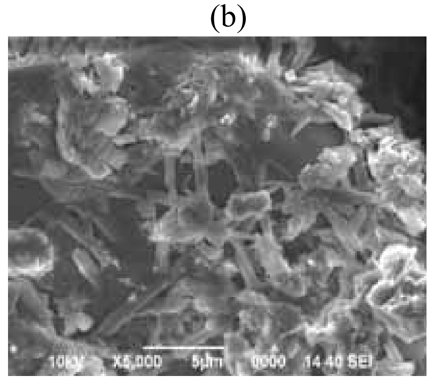


Fig. 2. Correlation between UCS and stabilizers

(a) (b)

(c) (d)

Fig. 3. SEM: (a) Untreated soil; (b) Untreated FA;
(c) FA + Soil; and (d) OPC + Soil

Drilled Displacement Piling in Soft Soil Conditions

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Abstract

Drilled displacement (DD) piles refers to and encompasses a specialized technology in which a cast-in-place bored pile is constructed using a process in which a specially designed tool is advanced into the ground using rotation and downward thrust to displace the in-situ soil radially outward into the surrounding formation such that there is little or no soil removal. DD piles have been used as structural foundation elements (e.g., to support column loading) and for ground improvement (e.g., column-supported embankments) on both commercial and public work type projects.

The maximum diameter and depth that can be achieved are directly related to the capability of the drill rig used to construct the DD piles. To date, DD piles have been constructed with diameters ranging from about 300 to 800 mm (12 to 32 inch) and to a maximum depth of approximately 35 m (115 ft). The allowable design load of DD piles has ranged between 650 and 1300 kN (145 to 300 kips), and are a function of the constructed pile diameter, structural characteristics and properties of the pile, confining stress, and strength of the bearing layer.

DD piles can be categorized into one of two main groups: a concrete-type pile or a steel-type pile. For concrete DD piles, after the drilling tool has achieved the desired depth for the piling, concrete or grout is injected under pressure into the void space as the tool is withdrawn. Reinforcing steel, if required to provide structural stiffness, is typically inserted after the tooling has been removed from the borehole. Concrete DD piles can be further listed as either partial or full displacement piles according to the installation method and/or the type/shape of tooling (Figure 1) used to create the pile, which can be grouped as essentially cylindrical or screw shaped (Figure 2). For steel DD piles, a permanent steel pipe connected to a sacrificial drill bit is installed into the ground (Figure 3a); internal steel reinforcement and concrete can be placed within the open inner space of the steel shaft (Figure 3b) to provide additional rigidity and structural strength.

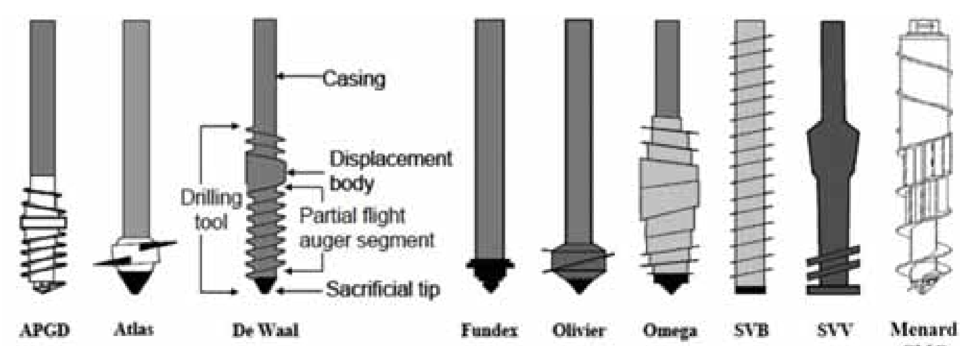
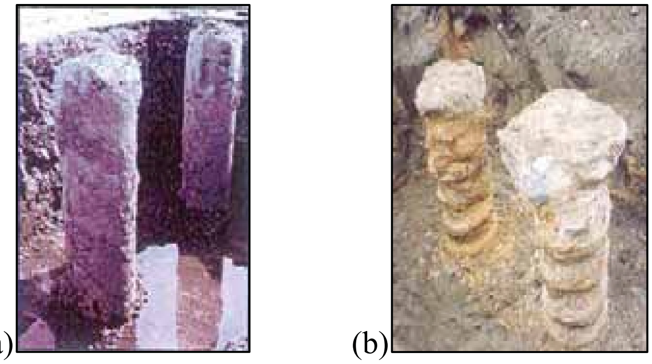
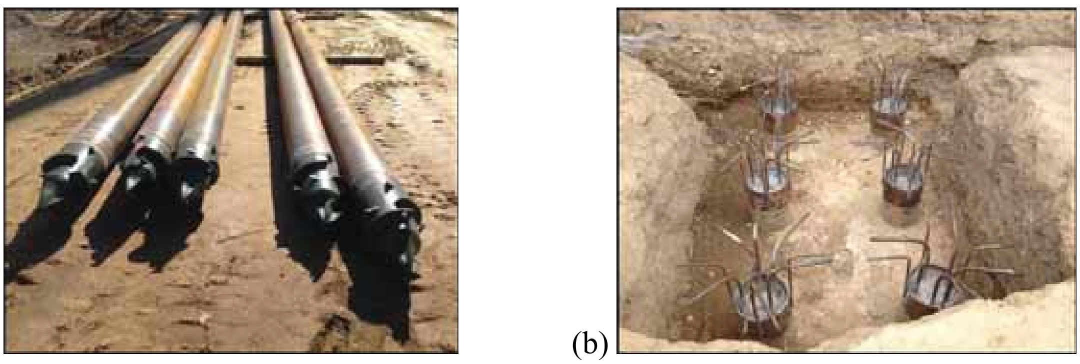


Figure 1. Schematic of different types of drilling tools for concrete DD piles (mod. after Basu and Prezzi, 2009)



(a) (b)

Figure 2. Photographs of (a) cylindrical and (b) screw shaped concrete DD piles (Marinucci and Chiarabelli, 2015)



(a) (b)

Figure 3. Photographs of (a) sacrificial drill bits welded to steel pipes and (b) internal reinforcement and concrete placed in open inner annulus of the steel pipe (Marinucci and Wilson, 2018)

In general, DD piles can be installed in ground conditions where the in-situ soils can be displaced and compacted. Therefore, this piling technique is applicable in soft-to-firm ground conditions – in loose to medium dense sands and in cohesive soils where the undrained shear strength is less than about 100 kPa (2,000 psf). However, greater ground improvement and load transfer benefits have been realized in loose-to-medium dense granular soils. The soil surrounding a DD pile will undergo changes to its stress state (e.g., change in void ratio) and matrix structure due to the torsional and vertical shearing stresses imposed by the tool during drilling the extraction. The amount of change is a function of various factors, including soil type, original stress state and consistency, shape of the tool, and installation method.

The empirical design methods that are available in the published technical literature (e.g., Bustamante & Gianeselli, 1998 and NeSmith, 2002) are based mainly on in-situ test results - unit base and shaft resistances related to CPT tip resistance (q_c), SPT N-value, or limit pressure (p_l) from the Pressuremeter Test (PMT). Given the competitive marketplace, the published methods provide a general understanding of designing DD piles, but contractors, understandably, are not willing to relinquish their competitive advantage (via proprietary installation methods) not will they will not divulge all of their secrets (and extensive experience and data). The main functions of DD piles are to increase soil density, improve (increase) bearing capacity, increase shear strength, distribute the load such that there is greater stress concentration on the pile and less stress on the soil, increase stiffness (reduce compressibility), and improve resistance to liquefaction.

The unique characteristic of DD piles is that they offer ground modification advantages along with load carrying characteristics of a deep foundation system. With this technique, the full ground improvement potential is mobilized during the densification of granular, cohesionless soils or during the compaction of cohesive soils. The load transfer characteristics of a DD pile are similar to deep pile foundation systems, and are achieved by transferring the loads thru weaker strata (e.g., soft cohesive, organic, and/or loose soils) down to more competent strata. A key benefit of DD piles is the minimal amount of drill spoils generated, which provides a cost effective and practical solution for sites with contaminated soils (e.g., typically found at landfills, brownfield sites, and industrial facilities). Other advantages of DD piles include larger unit values of side shear, stiffer pile response to loading, proven reliability, relatively rapid construction, high daily production, minimal operational noise and ground vibrations, and reduced environmental impact. Each of the benefits have contributed to the increased use of the technique especially for construction in urban areas, in congested spaces, and near existing structures.

Bio of Speaker

Dr. Marinucci is a principal at V2C Strategists LLC in Brooklyn, N.Y., executive editor of DFI Deep Foundations magazine, and lecturer at the Tandon School of Engineering at NYU. He received a Ph.D. degree in civil engineering (geotechnical concentration) from the University of Texas at Austin, and has MBA and MSCE degrees. Dr. Marinucci has more than 20 years of industry experience as a designer through construction manager on projects involving super and substructure design, geotechnical engineering, earth retention systems, deep foundation systems, and ground improvement systems. He is a registered professional engineer and is an active member of numerous professional organizations and technical committees, including the ASCE/GI, DFI, and TRB. Dr. Marinucci has authored or coauthored technical papers on design and construction applications, practical research, and legal issues relating to geotechnical engineering and the geo-construction industry.

Long-term performance of piled embankment

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Abstract

This abstract presents a series of full-scale model tests and numerical modelling on the long-term hydro-mechanical behaviors of piled embankment, including (1) the effect of cyclic loading on the soil arching and geosynthetic, (2) migration of water in embankment, and (3) the effect of water on the dynamic behaviors of embankment.

1. Loading cycles on soil arching effect and tensile force in geosynthetic. Under cyclic loading, the distribution of dynamic stress shows distinct soil arching effect in the piled embankment (Chen et al. 2014a, 2016b; Wang et al. 2018a, 2018b), as shown by the typical variation of dynamic stress along depth in Fig. 1. Based on the experimental results, the pile efficacy for dynamic stress is close to that for the static stress. A new method to calculate the distribution of dynamic stress in the piled embankment is proposed using the pile efficacy of static stress. On the other hand, as an additional reinforcement, the geogrid efficiently transfers the static load above the subsoil to the soils above pile cap (Wang et al. 2018b). However, the influence of the geogrid on the dynamic load transfer is not significant, because the tensile force cannot change simultaneously with the cyclic loading at such high loading frequency (Wang et al. 2018b).

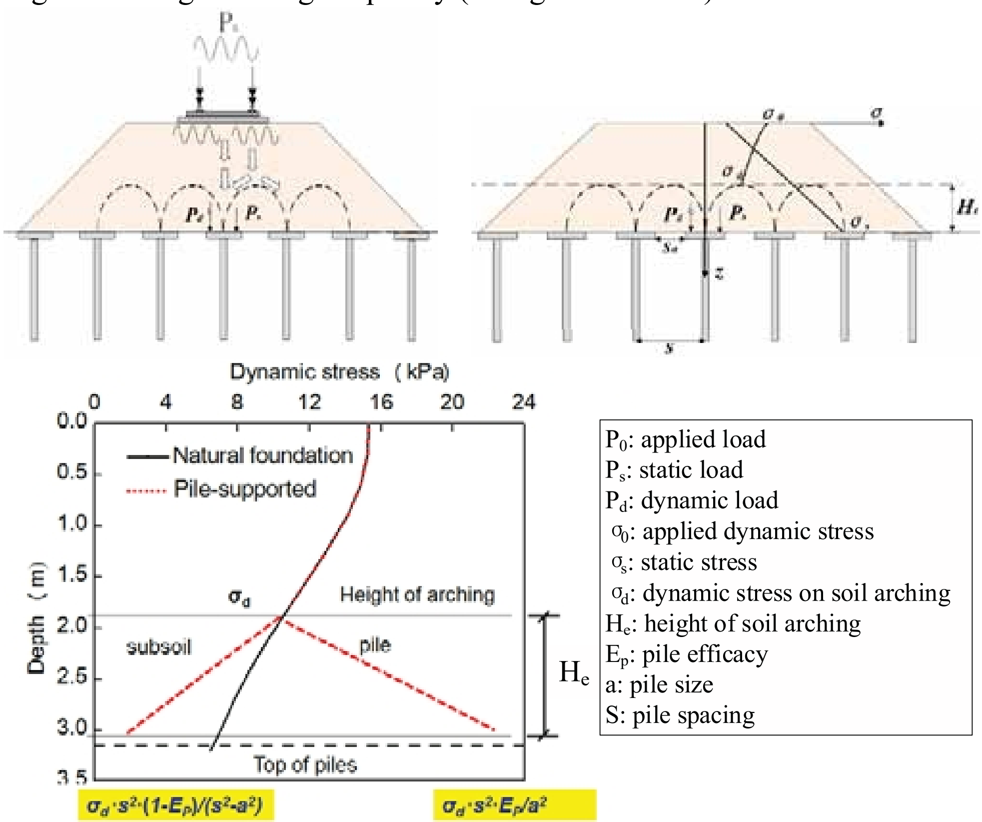

Fig. 1. Dynamic stress distribution and estimation in piled embankment

2. Migration of water in embankment. Using a large-scale infiltration column, the hydraulic properties of the embankment materials were evaluated (Chen et al. 2016c). Based on these parameters, moisture migration in the embankment was modelled for three years, with two fissures at the edges of concrete base (Wang et al. 2015; Chen et al. 2018). Under heavy rainfall condition, saturated zones develop in the embankment. With higher compaction degree or fines content of the subgrade soil, the size of saturated zone increases. The time for the wetting front to pass through the interface of surface layer and bottom layer is relatively long and drainage methods are needed to drain out the rainwater before infiltrating into the bottom layer.

3. The effect of water on the dynamic behaviors of embankment. With the rising of water level and cyclic loading at high water level, dynamic soil arching effect was found to increase (Wang et al. 2018b). At stable arching state (including water level lowering and loading at low water level), this effect tends to remain steady (Wang et al. 2018b). For the extreme case with elevated water level, the accumulative settlement of piled embankment was estimated using analytical methods (Chen et al. 2014b, 2016a; Wang et al. 2018a). The results show that the accumulative settlement mainly develops in the saturated zone under cyclic loading (Fig. 2a, Wang et al. 2018a). Furthermore, with the water level submerged to the top of embankment, large settlement more than 60 mm develops under cyclic loading (Fig. 2b, Chen et al. 2014b).

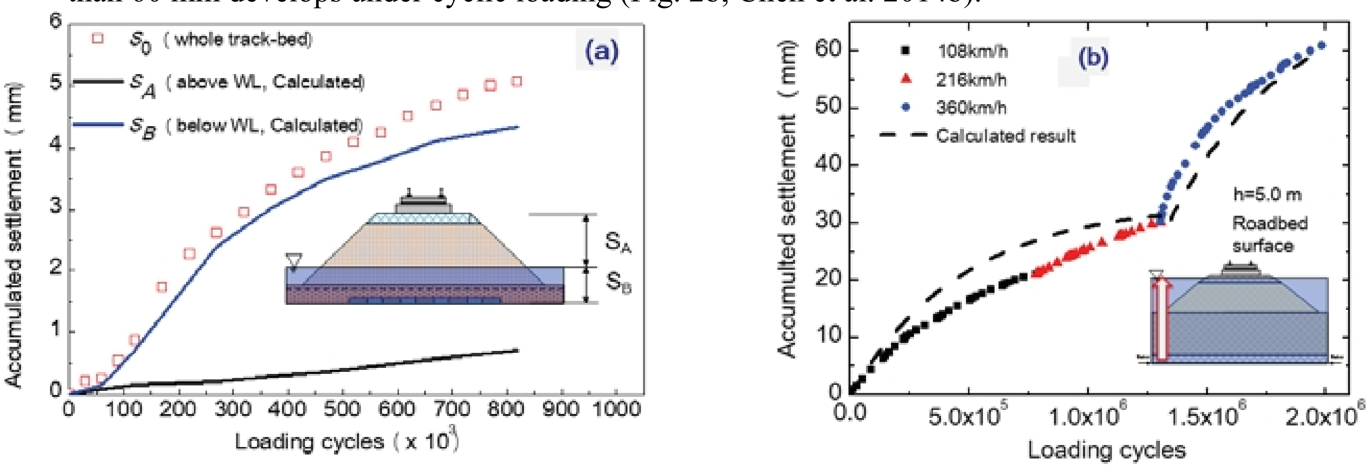

Fig. 2. Evolutions of estimated accumulative settlement with elevated water level

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Bio of Speaker

Dr. Renpeng Chen is a Professor specializing in Geotechnical Engineering in the College of Civil Engineering at Hunan University. Dr. Chen has research interests and expertise in characterization of pavement and railroad geomaterials, i.e., subgrade soils and foundation soils, soft soil improvement using piles, offshore pile foundation, TBM tunneling technologies. Dr. Chen has served as an investigator on over 50 research projects with grants received from national government agencies including Natural Science Foundation of China (NSFC), Ministry of Science and Technology (MOST), Ministry of Education (MOE); province government agencies, numerous design institutes and construction companies. Dr. Chen has graduated 8 PhD and 20 MS students, and authored/co-authored over 100 peer reviewed publications from his research projects. Dr. Chen is the associate Editor-in-Chief of China Journal of Highway and Transport, and editorial board member of 5 Journals including Chinese Journal of Geotechnical Engineering, Rock and Soil Mechanics, Journal of Zhejiang University-SCIENCE A, and so on. He is a member of Committee of Sustainability in Geotechnical Engineering (TC307), Asian Regional Technical Committee of Urban Geotechnics, of International Society of Soil Mechanics and Geotechnical Engineering, and vice chair of 3 technical committees of Soft Soil Engineering, Soil Constitutive Relationship and Strength Theory, Transportation Geotechnics, of Chinese Institute of Soil Mechanics and Geotechnical Engineering. Dr. Chen received Best Paper Awards of 2013 ISEV, 2016 Outstanding Journal Paper Awards of Journal of Performance of Constructed Facilities-ASCE, China Youth Science and Technology Award (200 persons every two years in China). He also received National Science Fund for Distinguished Young Scholars (100 persons every year in China), and was elected as Leading Researcher of Ten Thousand Talent Program in China (2016).

Applications of Multi-Shaft Deep Mixing Ground Improvement in the U.S. for Dam, Transportation and Shoreline Projects

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ABSTRACT

The Deep Mixing Method (DMM) is an in-situ soil treatment technology that introduces and mixes cementitious materials with native soils using hollow-stem rotating shafts equipped with a cutting tool at the tip and mixing paddles above the tip. DMM generally produces a soil-cement panel consisting of two to four overlapping soil-cement columns. The soil-cement panel is then extended to form walls, grids, or blocks for earth retention, seepage control, bearing capacity, settlement control, slope stabilization and liquefaction prevention. The first U.S. application of multi-shaft deep mixing was in 1987 for the foundation stabilization of Jackson Lake Dam in Wyoming. The presentation will illustrate the trend of multi-shaft deep mixing in the past 30 years using earlier and recent case examples in the areas of: 1) seismic remediation of earth dams, 2) foundation improvement for transportation infrastructure and 3) stabilization of shoreline facilities.

1. Seismic remediation of earth dams

1-1 Jackson lake Dam Modification – U.S. Bureau of Reclamation

An upstream soil mixing cutoff wall was installed to control foundation seepage and decrease uplift pressure. Soil-cement cells were installed along their entire length of upstream and downstream slopes to increase the shear strength of the foundation as shown in Figure 1-1.

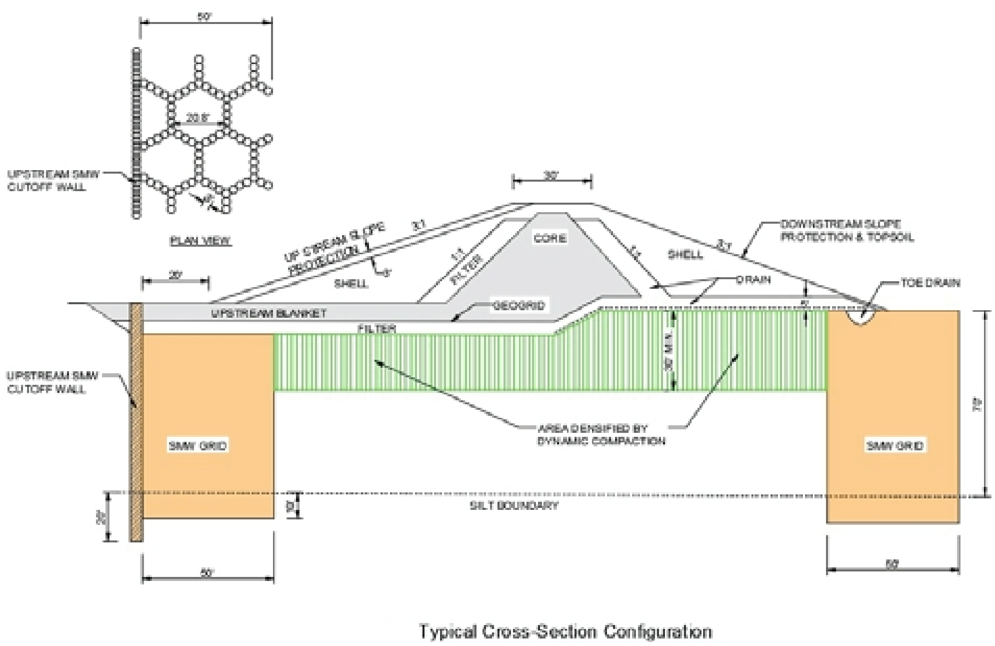

Figure 1-1. DMM installed using SMW Seiko equipment

1-2 Sunset Reservoir North Basin Dam Remediation – San Francisco Public Utilities Commission & Department of Safety of Dams (DSOD), California Department of Water Resources (DWR)

The site is located 5 km from San Andreas Fault. Geotechnical study revealed that the saturated native sands and silts could be susceptible to significant strength loss during a major earthquake. The DMM foundation stabilization consists of three rows of treatment blocks aligned parallel to the longitudinal axis of the embankment as shown in Figure 2.

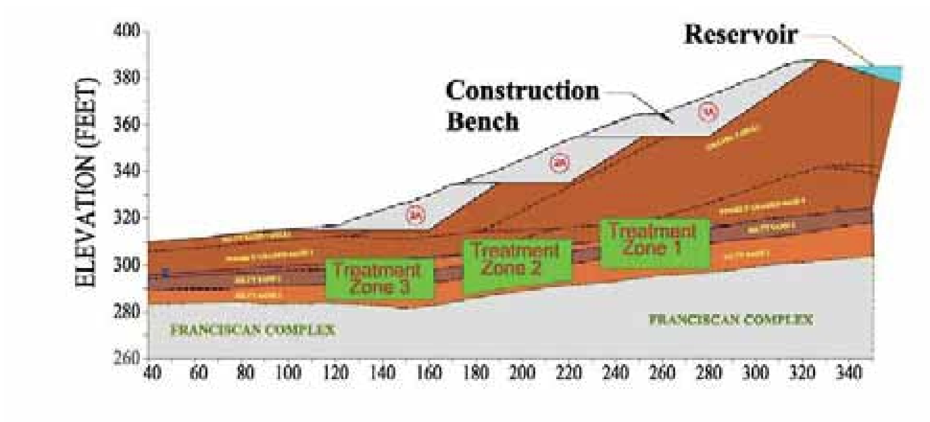

Figure 1-2. DMM installed by Raito, Inc.

1-3 Seismic Remediation of Perris Dam – DWR & DSOD

DMM cells are designed to maintain the seismic stability of Perris dam. DMM shear walls provide the resistance to the lateral force induced by the earthquake.

Figure 1-3

2. Foundation improvement for transportation infrastructure

2-1 Boston Central Artery / Tunnel Project – Massachusetts DOT

The interchange at Fort Point Channel consists of a network of tunnels and depressed roadway (boat section), viaducts and bridges requiring braced excavations as deep as 18.3 m (60 ft) in very soft to soft soils. DMM buttress was installed to maintain the stability of excavation for the construction of the underground transportation system (Figure 2-1).

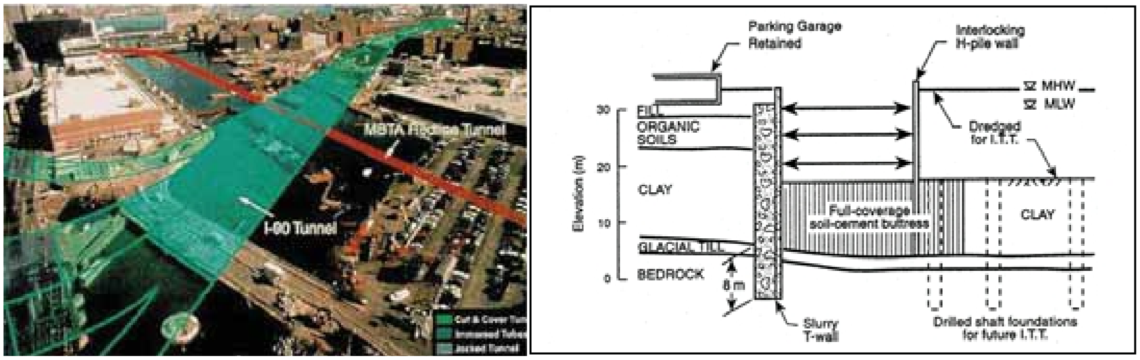

Figure 2-1. DMM installed using SMW Seiko equipment

2-2 Oakland Airport Roadway Project – Oakland Port Authority

DMM block was installed for maintaining the stability of excavation during construction. DMM block was then reinforced and combined with a concrete facing wall to serve as a long-term retaining structure of the underpass below a taxiway in Portland International Airport as shown in Figure 2-2.

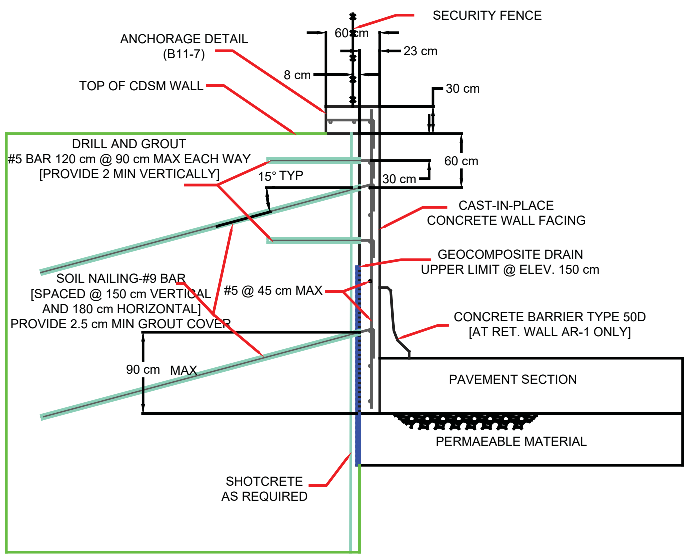

Figure 2-2 DMM installed by Raito, Inc.

2-3 Caltrans Broadway / HWY 101 Interchange Projects – California DOT

DMM shear walls were installed under the bridge abutments and retaining structures to maintain the stability and provide settlement control for the Broadway /Highway 101 interchange structure as shown in Figure 2-3.

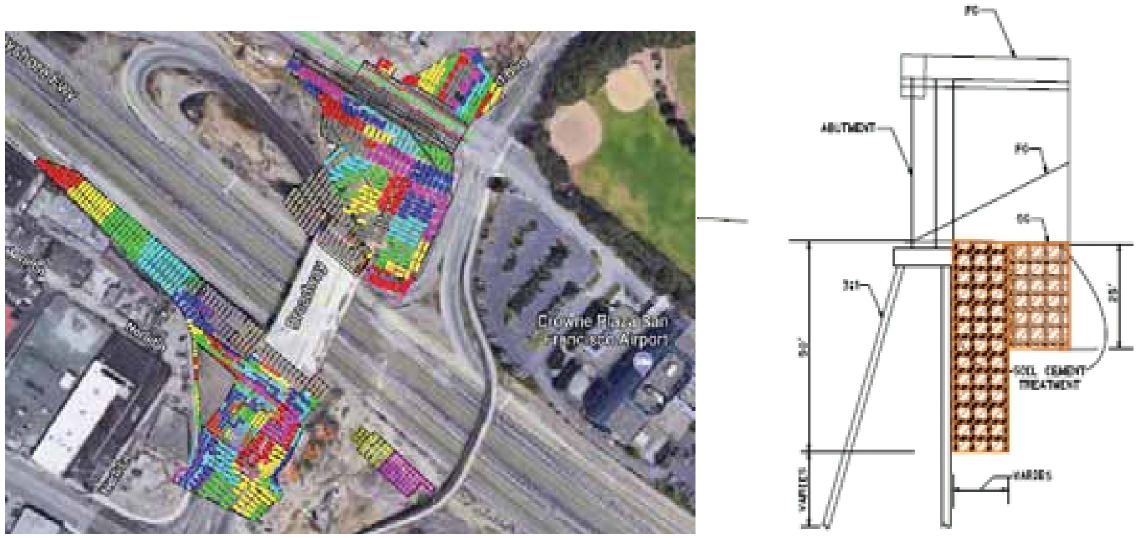

Figure 2-3

3. Stabilization of shoreline facilities

3-1 Port of Oakland Berths 55/56 & 57/58, CA – Oakland Port Authority

DMM cells were installed to maintain the stability of the cut slope for the deepening of Berths 55/56 and 57/58 in Port of Oakland. The treatment width and depth in historic slough area were increased to maintain the stability of the DMM cell structure as shown in Figure 3-1.

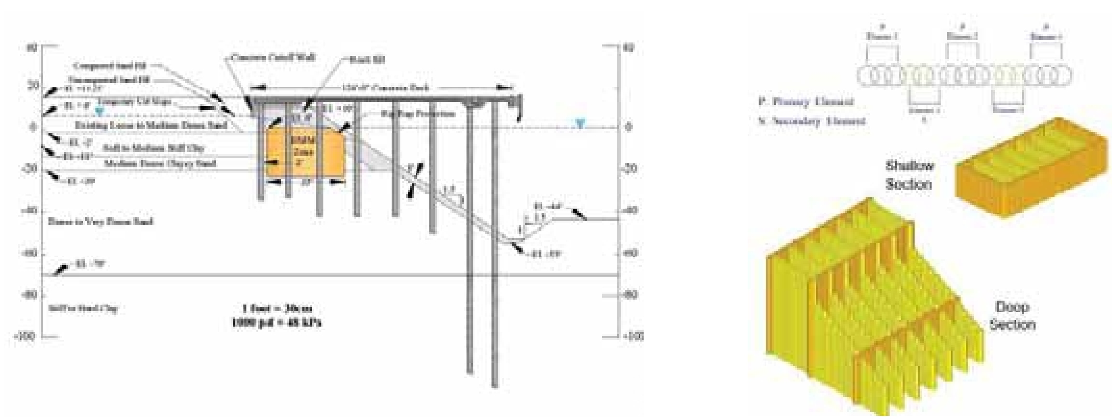

Figure 3-1. DMM installed by Raito, Inc.

3-2 Moin Container Terminal, Costa Rica – APM Terminals Moin S.A.

DMM cells were installed along the shoreline of a reclaimed land to maintain the stability of the cut slope for the construction of a new wharf. Three types of DMM cells were designed to cope with the configurations of the berth structure as shown in Figure 3-2.

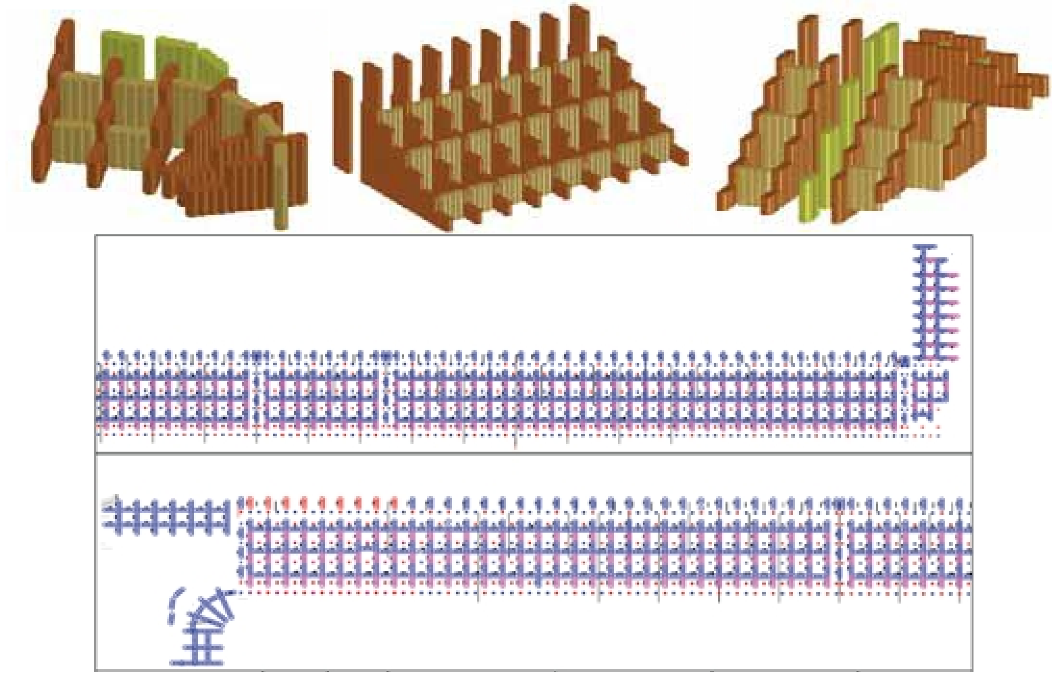

Figure 3-2

3-3 Blu Harbor Shoreline Stabilization, CA – RWC Harbor Communities

DMM longitudinal head walls and transverse walls were installed to maintain the slope stability along the shoreline of a reclaimed land over soft San Francisco Young Bay Mud for a residential development as shown in Figure 3-3.

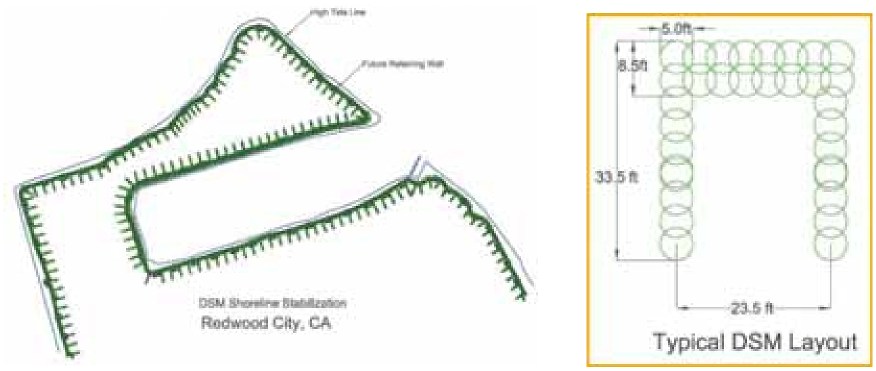

Figure 3-3

Bio of Speaker

Dr. David S. Yang is the Senior Vice President of JAFEC USA, Inc., a specialty company in the area of Soil Mix Wall method, Cement Deep Mixing method, Jet Grouting, Gravel/Sand Compaction Pile method and other ground improvement technologies. He received his Ph.D. in Civil Engineering from Purdue University in USA. He is a Licensed Civil Engineer and a Licensed Geotechnical Engineer in California. He is a Deep Foundation Institute (DFI) Deep Mixing Committee member. Dr. Yang is the co-author of the Federal Highway Administration Design Manual "Deep Mixing for Embankment and Foundation Support" published in October 2013 and the co-author of Chapter 3 - Mix-in Place Technologies of the book "Specialty Construction Technologies for Dam and Levee Remediation: The U.S. Technology Review" published in 2013. Because of his experience and knowledge in numerous soil mixing projects in the United States and Japan, Dr. Yang has become an invaluable resource for the engineers and designers who are planning or designing soil mixing projects.

Application of T-shaped cement deep mixed columns for soft ground improvement

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Abstract

Soil-cement deep mixing (DM) method is usually used to improve soft ground under an embankment load in China. In the construction of conventional DM columns supported embankment, soil-cement deep mixed (DM) columns are usually closely spaced. A compacted granular fill layer, or a geosynthetic reinforced layer, is placed over the top of DM columns, mainly to mitigate the differential settlement between DM treated soils and the surrounding untreated soils, and to increase the embankment stability. However, such a construction can lead to a significant increase in construction cost. In this study, a new type of DM column called T-shaped DM (TDM) column is proposed. This T-shaped column has an enlarged column cap at the shallow depth, resulting in the column shape being analogous to the letter ‘‘T’’(Fig.1). 1-g laboratory and full scale field loading tests were employed to investigate the vertical bearing capacity behaviour of a single T-shaped column in soft ground. After the loading test, several columns were excavated to investigate their failure modes (Fig.2). The results indicated that, since the section area of the column cap was remarkably higher than that of the deep-depth column, the stress concentration occurred in the deep-depth column just under the cap, leading to column failure. Based on this failure mode, a simplified method was proposed to estimate the ultimate bearing capacity of a single T-shaped column. the comparison of estimated and measured results indicated

The performance of the conventional DM columns improved soft ground under embankment load is also presented as a comparison(Fig.3). The difference of installation procedure, quality investigation, and in-situ plate loading test between TDM column and conventional DM column is discussed. Under the embankment loading, the stress concentration ratio, excess pore water pressure, total settlement, and lateral movement at embankment toe are also analyzed. It is concluded that the TDM method has merits of less cost while higher performance for soft ground improvement under embankment loading.

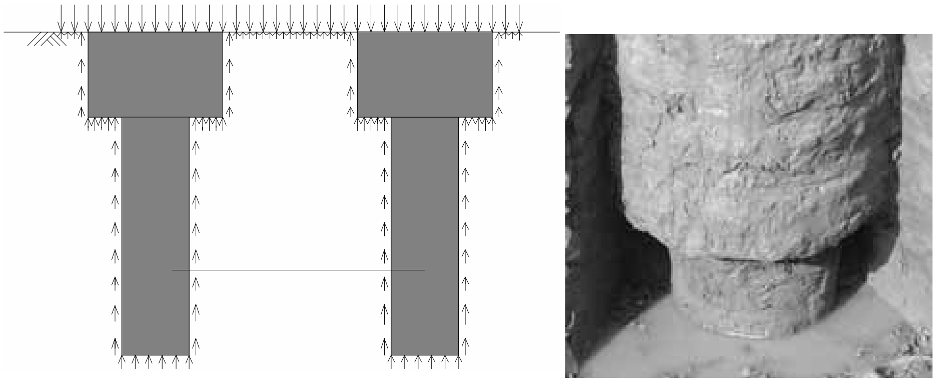

Fig. 1. T-shaped deep mixing column

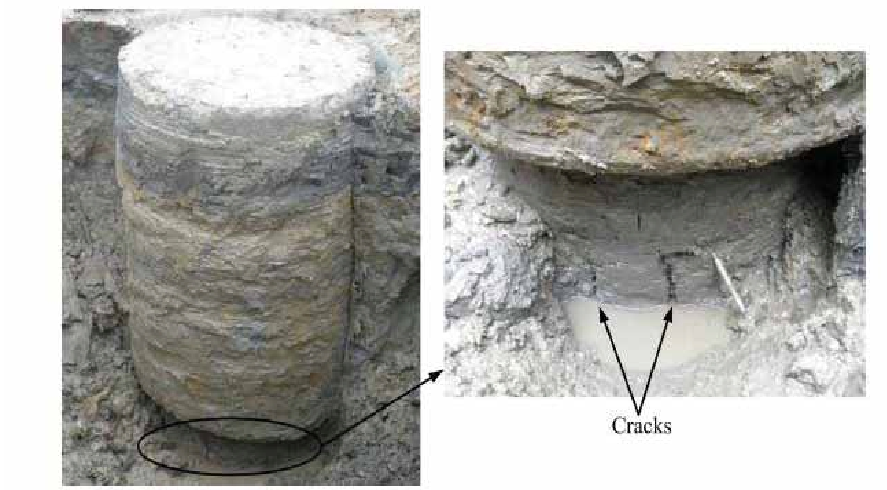

Fig .2 Excavated C1 column in Changzhou site after loading test

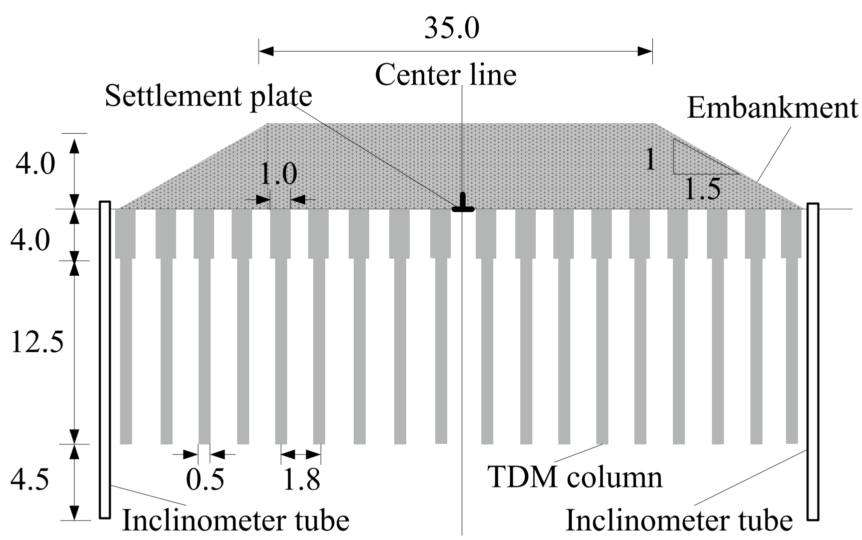

Fig. 3. Geometry design parameters of TDM columns (unit: m) at test site.

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Bio of Speaker

Dr. Song-Yu LIU is a professor of Geotechnical Engineering in Institute of Geotechnical Engineering at Southeast University in China. He received his Ph.D. in geological engineering from Nanjing University, China in 1991. His research interests include soil improvement, environmental geotechnology, in-situ testing method, and pile foundation. He is a member of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) and the American Society of Civil Engineering (ASCE); a vice president of Soil Mechanics and Geotechnical Engineering Institute, Chinese Society of Civil Engineering; a vice president of Ground and Foundation Engineering institute, the Architecture Society of China (ASC); and the director in Division of Foundation Engineering, Jiangsu Provincial Society of Civil Engineering and Architecture, China. Prof. Liu has published more than 200 journal papers (in English and Chinese) and 6 books (in Chinese).

Mechanism and Settlement of Geocell Reinforced and Stone Column Supported Embankment

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Abstract

Stone columns, as an economical foundation improvement technique, have been widely used to support loaded structures such as embankments. The strength and stiffness of the stone column are both dependent on the effective lateral confining stress provided by the surrounding soil. As a result, conventional stone columns are not recommended in very soft soils (undrained shear strength $\tau < 20$ kPa) due to the fact that such soft soils cannot provide enough lateral confinements. Geosynthetics, a new type of geotechnical material for engineering, provide an alternative for the treatment of soft soil. The problem of installing stone columns in soft soils with low undrained shear strength can be solved by encasing or wrapping the columns with high-strength geosynthetic reinforcements, referred as "geosynthetic encased stone columns" in literatures. Another effective way to solve the problem using geosynthetics is to place a geosynthetic-reinforced gravel cushion over the top of columns (referred herein as geosynthetic reinforced and stone column supported embankments).

For the recent decade, the Institute of Geotechnical Engineering of Hunan University concentrates on the investigation of the two-directional reinforced composite foundation where a geocell reinforced granular cushion is placed over the top of columns (as illustrated in Fig. 1).

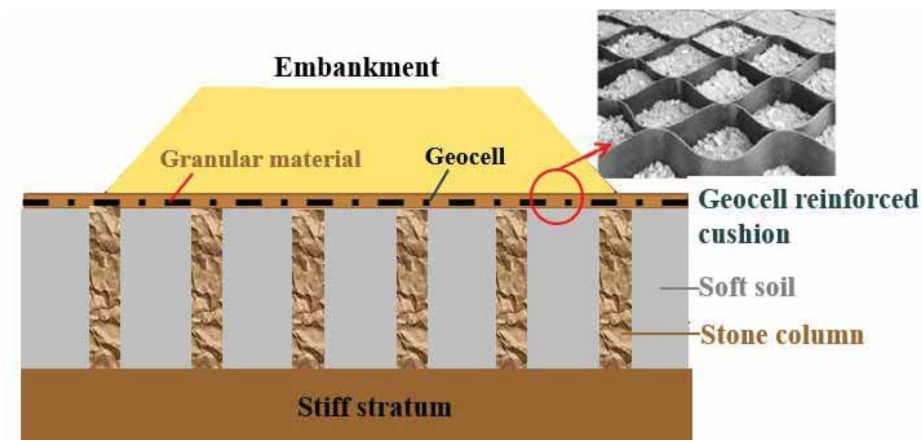
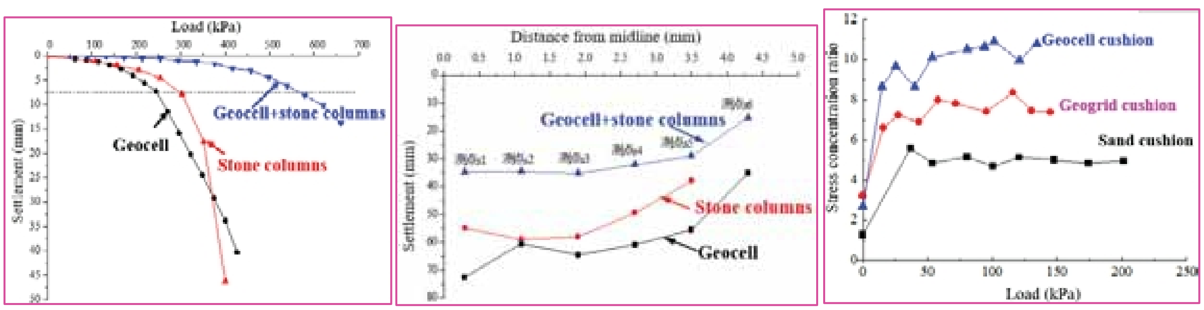


Fig. 1 Schematic of geocell reinforced and stone column supported embankment

In this technique, stone columns combined with geocell reinforcements would simultaneously make full use of their respective advantages, by which not only well drainage performance of the stone column could be preserved, but also further improvements in the bearing capacity and stability, and remarkable reduction in the total and differential settlements of foundation soil could be realized. Compared to the single-layer geogrid reinforced cushion, the geocell comprising of three-dimensional honeycombs interlocks with the internal gravel and other fillers to form a cushion structure, and the structure could work better as a stiffened working platform. This geocell reinforced cushion can effectively transfer and homogenize the load from the upper embankment and constrain the lateral spreading of the embankment. On the other hand, the two-directional reinforced composite foundation can overcome shortcomings of traditional single-reinforced composite foundation. The fact is that reinforcements within only vertical direction cannot guarantee the stability of high embankments, although it is capable of improving the bearing capacity and reducing the settlement for the foundation. On the contrary, reinforcements within only horizontal direction cannot substantially reduce the settlement and guarantee the stability of foundations.

A series of experimental studies have been conducted, including several large-scale laboratory model tests, it is concluded that: (i) as far as the improvement of the bearing capacity and the reduction of the settlement concerned, stone columns combined with geocells would more be efficient than a single stone column or a single geocell reinforced composite foundation (Figs. 2 (a) and (b)); (ii) The restrain for the lateral spreading provided by geo-reinforcements would inhibit the bulging of the stone column at its top; the occurrence of the bulging would be postponed and move downward, so that the carrying capacity of the stone column could be improved; (iii) reinforcements within horizontal direction can transfer more loads from embankments to stone columns, and mobilize the bearing capacity of stone columns more effectively; in particular, geocells could be more useful than the geogrid in enhancing the load transfer.



(a) *p*~*s* curves (b) Settlements (c) Stress concentration ratio

Fig.2 Experimental results

In the respect of settlements, the prediction of settlements for geocell reinforced and stone column supported embankments were proposed based on the assumption of Winkler elastic foundation within finite beam theory and the concept of matrix transmission, by including the stiffness difference between the columns and soils as well as the horizontal friction between the reinforcements and soils.

The proposed technique has been applied in the construction of Linchang Expressway in Hunan province. Compared with conventional methods, the bearing capacity of the foundation increased by 21% to 46% and the settlement reduced by 18% to 32% with the implement of stone columns with geocell.

Bio of Speaker

Zhang Ling received her Ph.D. degree of Civil Engineering from Hunan University in 2012. She currently works as an associate professor at the College of Civil Engineering in Hunan University. Dr. Zhang has been devoting to academic investigations of ground improvement and pile foundation, such as practical methods for the geosynthetic encased stone columns (GESC), geosynthetic reinforced and pile supported embankments, and laterally loaded piles. More than 60 academic papers, including 21 SCI papers, have been published on international and Chinese journals such as ‘Geotextiles and Geomembranes’, ‘Computers and Geotechnics’, ‘Journal of Engineering Mechanics, ASCE’, ‘International Journal of Geomechanics, ASCE’. Dr. Zhang has received the First Award of Science and Technology Progress in Hunan Province (2nd accomplisher, 2012) and the First Award of Science and Technology Progress in Zhejiang Province (3rd accomplisher, 2017). Her Ph.D. thesis was appraised as the Excellent Doctorial Dissertation of Hunan Province in 2014.