Modelling the advantages of the DSM (deep slurry mixing) technology on the piling process of the plug-in steel

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Abstract. The development of the bay area is restricted by the cross-sea communications. Recently, the bridge-tunnel system is a perfect solution for this question. The man-made island is a key connector in this system by connecting the bridge and tunnel, and creates a buffer zone of the communication. The plug-in steel cylinders are suitable structure for the construction of the man-made island due to its convenience, reliability, and low-cost. In practice, the sand layer and other hard soil layers challenges the piling of the cylinders, causing the structure failure of the cylinder and other problems. The pre-treatment with DSM (deep slurry mixing) technology is an effective way to improve the piling process. This paper models and analyzes the piling of the cylinder through the sand layer treated by DSM technology with in-site tests and numerical simulation method. The advantages of the DSM technology are highlighted and quantificated to make a contriobution in practice.

1. Introduction

The plug-in steel cylinder is well suited in the construction of the man-made island in the cross-sea bridge-tunnel system for its convenience, reliability and low-cost. The plug-in steel cylinder can quickly form the bulkhead wall of the man-made island in the deep-water area without underwater excavation. In practice, the vibration driving is the common piling way [1]. The side and tip resistance are reduced by the vibration and the steel cylinder penetrates the soil layer under the action of weight and inertia force [2]. Xu et al. [3] analysed the piling process of the steel cylinder in the muddy soil layer with Japanese code, PTC code of France, ICE code of America, pile pressure coefficient method, wave equation, and other methods. Vipulanandan et al. [4] analysed the influence of the initial density of the sand on the piling speed in sand layer. Zhang [5] pointed that the dynamic viscous damping force affects the stress and deformation of the sand. Xu [6] modelled the piling process of the steel cylinder with the non-linear viscoelastic spring element. Li [7] studied the static sinking of the cylinder and proposed a new resistance assessing equation during the sinking process.

At present, most research focus on the piling through the soft soil layer, which is also the most common scene in engineering practice. While more and more pilings in sand layer happen in recent
engineering cases, and the potential risk of the structure failure of the steel cylinders in these vibration piling process increases. This paper analysed a new technology for improving the piling in sand layer. In-site testing and numerical simulation were carried out to obtain the key parameters during piling for evaluating the benefit of the DSM (deep slurry mixing) technology.

2. Brief introduction of the engineering case
The Shenzhen-Zhongshan tunnel case locates at the Zhujiang River, and the total length is 24.03 km with 22.39 cross-sea section. The western man-made island is on the west of the Fanshi channel, forming by 57 cylinders with 28 m wide outer-diameter and different heights. Due to the influence of the dredging, the distribution of the soil layers is uniform and different soil mix with each other. The silty clay mixed sand layer widely exists in the engineering area, and the thickness varies from 0 m to 9.1 m. The blow count of standard penetration test of this layer reaches 35, and this layer becomes much denser due to the vibration according to the in-site test, making the cylinder impossible to punch through without structure failure. Therefore, this layer must be treated before the piling of the steel cylinder.

3. In-site testing on the improvement of the soil layer caused by DSM technology
The DSM technology was conducted by the DSM boat. The slurry, which is formed by water, bentonite clay, is injected and mixed with the sand layer to soften the origin soil layer. The resistance of the sand layer after treatment is also tested with standard penetration test (SPT). And the blow count of the SPT before and after DSM treating is listed in Table 1.

| Testing sample NO. | X19-1 | X22-1 | X23-1 |
|-------------------|-------|-------|-------|
| Thickness of the soil layer (m) | Before treating | 5 | 3.5 | 3.3 |
| After treating | 0 | 0 | 0 |
| Blow count of SPT (-) | Before treating | 5~18 | 32~43 | 30~39 |
| After treating | <1 | <1 | <1 |

The blow count of SPT for each sample reduces after being treated with DSM technology. The silty clay mixed sand layer in X19-1 sample was changed to mud and silty clay layer, and the blow count of SPT reduces to less than 1. The gravel sand layer in X22-1 sample was changed to mud and silty clay layer, and the blow count reduced from 32-43 to less than 1. In addition, part of the weathered rock, which is more than 50 blow counts in SPT and near the gravel sand layer, was changed to silty clay, showing the DSM technology has the ability to improve the hard soil with more than 50 blow count. The gravel sand layer in X23-1 sample was changed to mud layer, and the blow count reduced from 30-39 to less than 1. In practice, all cylinders were piled smoothly after the DSM treating was conducted.

4. Simulation of the piling process after treating with DSM technology
The PLAXIS 3D software was used in numerical simulation to analyze the influence of DSM technology on the piling process. The finite element model was shown in Figure2. The soil model was 300 m long and 15 m wide, simulating with soil element. The Mohr-Coulomb stress-strain relationship was used to model the soil. Table2 shows the parameters of soil layers. The outer diameter of the cross-section of the steel cylinder is 28 m, and the cylinder, which is modelled with plate element, is 28 m high in total. The elevation of the top of the cylinder is +3.34 m. Table 3 shows the parameters of steel cylinder.
Table 2. The properties of the soil

| Soil layers                        | Elevation of the soil layer (m) | Weight (kN/m³) | Young’s modulus (kPa) | Poisson’s ratio (-) | Cohesion (kPa) | Inner frictional angle (°) | Permeability coefficient (mm/d) |
|------------------------------------|---------------------------------|----------------|-----------------------|--------------------|----------------|--------------------------|-------------------------------|
| 2-1 Mud                            | -13.5 ~ -22                     | 15.5           | 8387                  | 0.38               | 5.4            | 8.7                      | 0.35                          |
| 2-2 Silty clay                     | -22 ~ -23.5                     | 19             | 30000                 | 0.3                | 15.8           | 18.1                     | 1.7                           |
| 3-6 Medium sand                    | -23.5 ~ -31                     | 19.7           | 96570                 | 0.3                | 12.9           | 33.7                     | 500                           |
| 3-2 Silty clay                     | -31 ~ -32.5                     | 19.2           | 32610                 | 0.3                | 20.5           | 16.4                     | 1.7                           |
| Weathered rock                     | -32.5 ~ -50                     | 19.5           | 13370                 | 0.3                | 20.5           | 29.4                     | 10                            |
| Backfilled sand inside of the cylinder sand compaction pile | /                              | 16.7           | 8980                  | 0.3                | 2              | 28                       | 288                           |
| Sand layer after treating by DSM technology | /                              | 25             | 30000                 | 0.25               | 1              | 35                       | 500                           |
| /                                  | /                              | 19             | 1246                  | 0.3                | 4              | 20                       | 50                            |

Figure 1. The FEA model

Table 3. The properties of the cylinder

| Thickness (m) | Weight (kN/m³) | Stiffness (GPa) |
|---------------|----------------|-----------------|
| 0.02          | 68             | 50              |

The axial force, shearing force, and the bending moment for cylinders with and without DSM treating are shown in Figure 3, 4, and 5 and the maximum values are concluded in Table 4

Figure 2. The distribution of the axial force N1 for cylinder piling with and without DSM treating
Comparing to the soil without DSM treatment, the steel cylinder can penetration through the soil layer treated with DSM technology easily. The axial force, shearing force, and bending moment reduces a lot after DSM treating.

Table 4. The stress of cylinder during the piling process through sand layers with and without DSM treating

|                      | Without DSM treating | Treated with DSM | Reduction (%) |
|----------------------|----------------------|------------------|---------------|
| Axial force N1 (kN)  | 988                  | 15.8             | 98.4          |
| Axial force N2 (kN)  | 605                  | 105              | 82.6          |
| Shearing force Q12 (kN) | 570            | 48               | 91.6          |
| Shearing force Q23 (kN) | 284            | 10               | 96.5          |
| Shearing force Q13 (kN) | 153            | 7.4              | 95.2          |
| Bending moment M11 (kN·m) | 5.8         | 0.09             | 98.4          |
| Bending moment M22 (kN·m) | 2.4         | 0.03             | 98.8          |
| Bending moment M12 (kN·m) | 0.8         | 0.04             | 95.0          |
5. Conclusion
The influence of the DSM technology on the piling of cylinder was analysed with in-site test and simulation method in this paper, the main conclusions are as followed.

(1) The DSM is conducted by DSM boats. The mixed slurry was injected and mixed with the origin soil layer to reduce the blow count of the origin soil layer to improve the piling of the steel cylinders.

(2) The blow count of sand layer and other hard soil layers was deeply reduced after DSM treating according to the data from in-site tests. The DSM can also be used to treat weathered rock with more than 50 blow counts.

(3) The axial force, shearing force, and bending moment of the steel cylinder during the piling stage reduces more than 82% comparing to soil layer before DSM treating, heavily reducing the potential structure failure generated in piling stage.

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