Engineering Geology 181 (2014) 169–179

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Technical Note

Densification of loosely deposited soft soils using the combined consolidation method

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ARTICLE INFO

Article history:
Received 15 March 2014
Received in revised form 8 July 2014
Accepted 13 July 2014
Available online 18 July 2014

Keywords:
Combined consolidation
Lower-energy dynamic consolidation
Vacuum dewatering
Depth of improvement
Allowable bearing capacity

ABSTRACT

Dynamic consolidation (DC) has been widely used for a variety of soil types and conditions, particularly for soft soils, due to its superior results and low cost. However, soft soils become 'rubbery soils' when the groundwater table is high and the single DC method is used. In this paper, the combined consolidation (CC) method was applied to a site with loosely deposited soft soils in the Yangtze River Delta of China. This method integrates two technical construction characteristics, low-energy DC and vacuum dewatering. To properly manage these soil conditions and optimize the CC design, field tests were conducted to determine the factors that influence CC. Deformation tests that consider ground settlement, pore water pressure, and the groundwater table were performed to obtain rational construction parameters and to provide proof regarding the adjustment of the original CC procedure. Drilling sampling and cone penetration, surface wave, and plate loading tests were conducted to evaluate the overall effects of CC. The allowable bearing capacity and the depth of improvement at the site were estimated to exceed 120 kPa and 6 m, respectively. Both of these values meet the design requirements.

1. Introduction

Loosely deposited soft soils are widely distributed along the Yangtze River and its tributaries in China. Soft soils are composed of clay minerals, mainly illite and chlorite. In addition, these soils are highly compressible with large void ratios and low structural strengths. The natural microstructure of the soil is dense-open and disoriented granular–laminar with short linkages. When subjected to loading stress, the density of the microstructure and the number of contact points are generally proportional to the applied stress (Xia et al., 2006). Consequently, a large amount of differential settling occurs when a soft soil is used as a foundation. Thus, appropriate treatment methods should be used before constructing on soft soils.

Currently, the main methods for treating soft soils include the replacement method, which uses dry jet mixing piles or cement fly-ash gravel (CFG) piles, and the drained, dynamic, or combined consolidation methods (Zhang et al., 2011). Furthermore, cushioning is a shallow traditional treatment method that can reduce the compressibility of soft soils after backfill and compaction. The cushioning method is generally suitable for treating small-scale foundations. However, this method is expensive and requires large amounts of excavation and fill and a long construction period. The dry jet mixing piles (or reinforcing soil piles) method is a deep mixing method that is used to reinforce foundations. This method uses powder to form a curing agent for treating the soft foundation. Although this method is common and effective, its use is limited due to its high cost. The drainage consolidation method involves placing a network of closely spaced vertical foraminous pipes into the soil and applying a surface load to squeeze out and drain the moisture through the pipes. This process consolidates and strengthens soft soils. However, because the drainage consolidation method often requires considerable time, it is not widely adopted (Editor Committee, 1994). Dynamic consolidation (DC), which is known for its versatility regarding a range of soil conditions, is one of the most widely adopted methods for large-scale soil treatment (Menard and Broise, 1975). However, the 'rubbery soil' and consolidation effects are controversial if the job site has a high groundwater table (Zhou et al., 2003; Deng and Xu, 2010). To obtain effective consolidation quickly and cheaply, low-energy DC and vacuum dewatering are integrated to form a new method, the combined consolidation (CC) method. The DC method involves destroying the soil grain skeleton, decreasing the porosity, and packing the ground through dynamic vibration. In addition, vacuum dewatering involves the formation of a vacuum and lowering the groundwater table. Both of these methods reduce the soil compressibility and increase the allowable bearing capacity of the foundation soil. Fig. 1 contains a schematic of the CC method, which involves using vacuum dewatering and DC in repeated runs. As with DC, the factors that influence the CC design can be divided as follows (Feng et al., 2010): the ground property and the CC technique aspects. The ground properties include the soil type, groundwater table, and underlying compressible layer, and the CC technique includes the tamping energy, grid pattern, number of impacts, number of drops, termination criterion at each point of impact, and the time delay between the passes.

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http://dx.doi.org/10.1016/j.enggeo.2014.07.010
0013-7952/

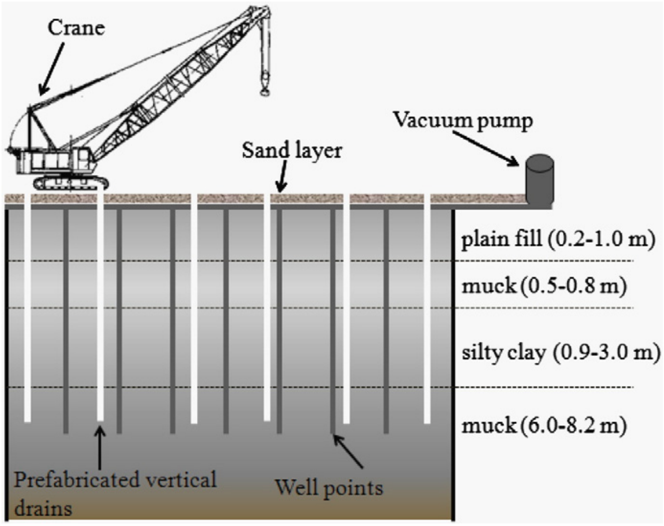

Fig. 1. Schematic of the CC method.

The CC method has been increasingly used in various areas, especially in China, due to its low construction costs and short construction time for the consolidation of soft soils (Zhou et al., 2005; Chen, 2010; Liang and Xu, 2012). However, research regarding the use of the CC method has previously remained scarce despite the method's increasing use. Thus, some investigations regarding DC and vacuum dewatering serve as a reference for designing the CC method. The principles and mechanism of vacuum dewatering were first described by Kjellman (1952). Mohamedelhassan and Shang (2002) proposed an analytical solution for one-dimensional consolidation and vacuum application. Indraratna et al. (2005) extended the unit cell radial consolidation theory for vacuum application with instantaneous loading by considering the vacuum loss along the length of the drain. Lo et al. (1990) suggested an improved and empirical approach for selecting operational parameters for DC. Chow et al. (1994) proposed a simplified model based on the one-dimensional wave equation for predicting the crater depth associated with decreased weight. This model also allowed users to determine the depth and degree of soil improvement beneath the impact zone. Arslan et al. (2007) demonstrated the effects of tamper weight shape on using the DC method in granular soils. Furthermore, the finite element method was recently used to simulate the DC of loose soils (Pan and Selby, 2002).

Many studies have discussed DC and vacuum dewatering. However, the design and application of these systems remain largely empirical in nature and primarily rely on the designer's practical engineering experience. In addition, a remarkable difference exists between the theoretically calculated and measured values. Moreover, the estimates obtained from the empirical method may vary significantly and are often useless (Poran and Rodriguez, 1992). Because of these issues, a pilot test must be conducted at each potential site to determine the most reasonable operational parameters and to minimize the operational costs (Chow et al., 1994; Shui, 2004; Miao et al., 2006; Feng et al., 2013).

This paper presents a field study in which the designed CC procedure is rationally adjusted and the effectiveness of CC is evaluated for backfilled soil. Prefabricated vertical drains were buried in the soil to verify their benefits regarding the effects of CC (Arulrajah et al., 2013). Several in situ tests were conducted, including deformation tests, pore water pressure (PWP) measurements, groundwater table monitoring, cone penetration tests (CPTs), spectral analysis of surface wave (SASW) tests, and plate loading tests. To optimize the CC procedure, settlement and ground heave were monitored during its use to determine the rational impact spacing and the optimal number of drops per pass. In addition, the PWP was monitored to determine the time delay between the passes. Drilling sampling tests, CPTs, and SASW tests were performed to evaluate the depth of improvement after using the CC method. Finally, the allowable bearing capacity was validated after employing the CC method using drilling sampling and plate loading tests. This interesting case study extensively monitored and tested the CC method in the field and could be used for the design and evaluation of current ground improvement methods.

2. Site characterization and subsoil conditions

The proposed project site is located in the Yangtze River Delta in Taicang city, Jiangsu Province, China, and covers an area of 0.298 km^2. The construction site featured an industrial workshop that included factories, warehouses, and offices. The ground surface, which contained a certain cultivated soil depth, was relatively flat at the time of construction, as shown in Fig. 2. The groundwater table at the site varies between 0.8 and 1.38 m and fluctuates less than 1.0 m under the influence of atmospheric precipitation and surface water. Before consolidation, a preliminary geological investigation was conducted by drilling boreholes. The average physical and mechanical properties of the subsoil are provided in Table 1.

Due to the high groundwater table and large site area, traditional methods, such as cushioning and DC, were not appropriate because they were expensive and potentially ineffective. The CC method was implemented to improve the soil conditions. In practice, the performance design and application of the CC method are largely empirical in nature and rely heavily on the designer's experience and judgment. Therefore, a pilot test was conducted at the site before implementing the CC method to determine the key design parameters. The minimum design criteria for the allowable bearing capacity and improvement depth after the CC treatment were 120 kPa and 6.0 m, respectively.

3. CC design and testing procedure

The test zone was 50 m × 50 m and was backfilled with 0.8 m-thick barged-in fill sand. In addition, the test zone was divided into T1 and T2, with T1 consolidated by the CC method, and T2 consolidated by the CC method with a prefabricated vertical drain. Fig. 3(a) presents the original layout of the prefabricated vertical drains, well points, and observation points for the T1 and T2 test zones. Trial tamping was conducted in the trial zones near the test zone (numbered T3 and T4) to select better design parameters, as shown in Fig. 3(b) and (c). The T3 trial zone was consolidated by low-energy dynamic consolidation (LEDC). Furthermore, LEDC was used with prefabricated vertical drains in the T4 trial zone.

Fig. 2. Site soils under CC.