Engineering Geology 246 (2018) 1–11

Contents lists available at ScienceDirect

Engineering Geology

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

Investigating the resonance compaction effect on laterally loaded piles in layered soil

Hongjiang Li[a,b], Songyu Liu[a,c,*], Liyuan Tong[a,c,*], Xiangchun Xu[a,c]

[a] Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, China
[b] Centre for Offshore Foundation Systems, The University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia
[c] Jiangsu Key Laboratory of Urban Underground Engineering & Environmental Safety, Southeast University, Nanjing 210096, China

ARTICLE INFO

Keywords:
Resonance compaction
CPT
Piles
Lateral response
Field testing

ABSTRACT

A case history of the Old Yellow River deposits where ground improvement was implemented by the resonance compaction method (RCM) is presented. The soil profile consisted of a silt layer and a silty sand layer overlying a clay layer. Located in a region with high-intensity earthquakes, the silt layer and silty sand layer are prone to liquefaction, thereby resulting in structural distress and failure. The treatment effect and soil liquefaction possibility prior to and after compaction were evaluated using the CPT and SPT approaches. The increase in the horizontal soil effective stress after compaction reflected by the change in CPT sleeve friction was examined. In addition, a series of full-scale field tests were conducted to study the lateral bearing behaviour of pile foundations in compaction-improved layered soil. The comparison of load-displacement, internal force and bending moment, as well as the soil reaction before and after compaction, was performed in detail. The effect of the resonance compaction on laterally loaded piles and its advantages compared to untreated soils were analysed. It is concluded that the RCM can significantly strengthen the weak soil conditions and improve the performance of laterally loaded piles.

1. Introduction

Piles have been used widely for the foundations of many kinds of infrastructure and structures. The lateral response is a complex problem involving nonlinear interactions between the pile and the surrounding soil. In the design process, a main objective is to restrict the lateral pile deformation not exceeding the critical deformation value. This is easy to implement in good condition soils. For weak soils (e.g., liquefiable sands and soft clays), however, the control of displacement requires additional engineering measures. The most direct method is to increase the pile number or increase the pile diameter, which will greatly increase the cost. An innovative, more cost-efficient solution is to improve the stiffness and strength of the soil surrounding the pile foundation through ground treatment. The common ground treatment methods include the stone column method (Barksdale and Bachus, 1983; Han and Ye, 2001), dynamic compaction method (Mayne et al., 1984; Feng et al., 2015, 2017), grouting method (Winterkorn and Pamukcu, 1990), mixing method (Shen et al., 2003; Liu et al., 2012), deep vibratory compaction (Anderson, 1974; Broms and Hansson, 1984), and resonance compaction method (RCM) (Massarsch, 1991a; Liu and Cheng, 2012; Massarsch and Fellenius, 2017). Among them, the application of the first four methods is more common, but there are technical problems such as the packing need, the high cost and the large impact on the surrounding environment. The resonance compaction method adapted from deep vibratory compaction was firstly introduced in the early 1980s (Massarsch and Broms, 1983; Massarsch, 1991a). It was enhanced by changing the operating frequency of the vibrator to match the resonance frequency of the vibrator-probe-soil system. In the 1990s, Massarsch (1991a) proposed the concept of resonance compaction design and presented a mature technique for liquefaction soil treatment by using the resonance compaction method. Subsequently, different compaction probes including lightweight perforated probes were developed and used for liquefaction mitigation (Neely and Leroy, 1991; Massarsch, 1991b; Van Impe et al., 1994). To date, the resonance compaction method has been recognized as an efficient ground treatment technology. The application principles of resonance compaction in engineering practice have been described by Massarsch and Fellenius (2005). Some resonance compaction cases for improving sand fills and liquefaction mitigation are presented by Choa et al. (2001) and Massarsch and Fellenius (2017). In China, geotechnical engineers began to focus on the RCM technique from 2007 and developed a successful cross-wing vibratory probe at Southeast University of China (Liu et al.,

* Corresponding authors at: Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, China.
E-mail addresses: liusy@seu.edu.cn (S. Liu), 101010519@seu.edu.cn (L. Tong).

https://doi.org/10.1016/j.enggeo.2018.09.019
Received 27 April 2018; Received in revised form 17 September 2018; Accepted 18 September 2018
Available online 24 September 2018
0013-7952/

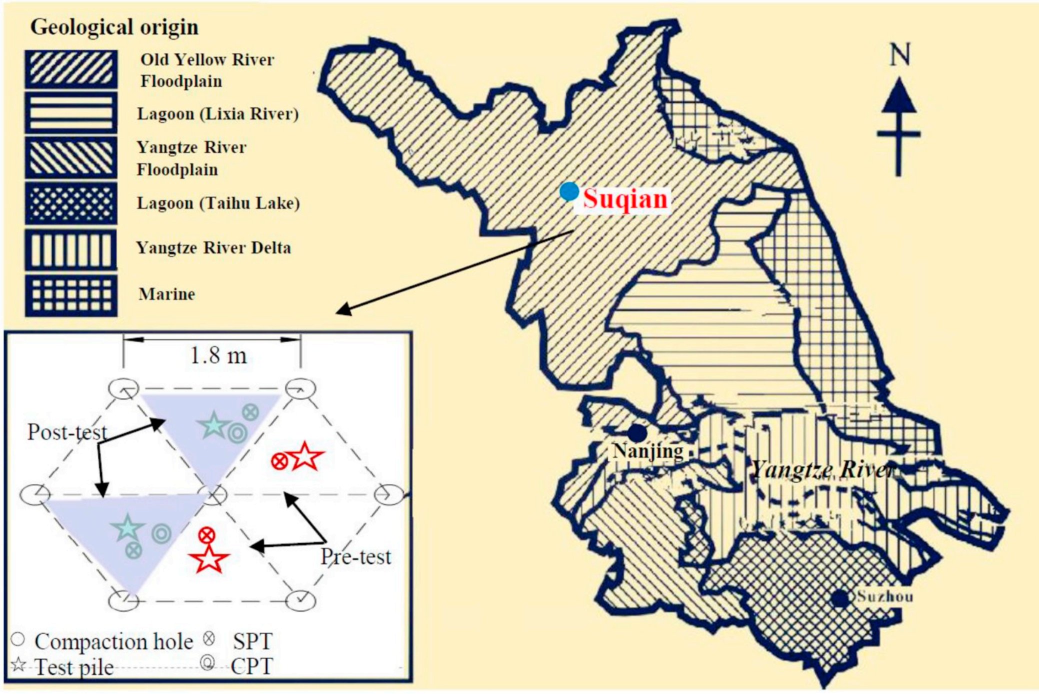

Fig. 1. Location (with layout of test points) and geological origin of the sedimentary units around the test site in the Suqian field of Jiangsu Province.

2008). The cross-wing resonance compaction method has the advantages of being light weight, highly efficient and simple to operate, and it has been applied to many projects in high-intensity earthquake areas in China. For pile foundation construction, Ohtsuka et al. (2004) analytically showed that improving the surrounding soil at a weak site can reduce the foundation cost by 28% because the lateral resistance of the foundation is increased. Despite the growing number of resonance compaction projects, to date, few existing experimental studies have focused on the behaviour of laterally loaded piles in improved weak soils by the resonance compaction method.

The present paper reports a series of in situ tests and full-scale field tests conducted to investigate the compaction effects on the lateral pile–soil interaction in layered soil. Based on the measured results, the lateral behaviour of the test piles after compaction and the comparison to the behaviour before compaction are studied.

2. Project site and subsoil profile

The full-scale tests were performed in Suqian city of Jiangsu province in eastern China, as shown in Fig. 1. The test site belongs to the typical Old Yellow River floodplain, which is located in the Jiao-Lu fault zone, with an 8-degree seismic fortification intensity and a 0.30 g basic earthquake acceleration. The earthquake group was classified as the first group. The equivalent shear wave velocity within 20 m depth of the soil layers is V_{se} = (168.3–194.6 m/s). The periodic value of the seismic response spectrum is 0.45 s. Within the compaction depth range, the soil profile consists of a silt layer and a silty sand layer overlying a clay layer. The groundwater table (GWT) is maintained 2 m below the ground surface. The silt layer and silty sand layer are prone to liquefaction under earthquake action at this site. Table 1 presents the detailed soil properties concluded from in situ (drill hole sampling, SPT, and CPT) and laboratory tests including conventional physical experiment, consolidation test, and triaxial test. The total thickness of the silt layer and silty sand layer are approximately 9–17 m for the whole stratigraphic distribution. The clay layer has a liquidity index of approximately 0.76 and a plasticity index of approximately 17.5. In addition, bored piles were used at the test site with a diameter of 600 mm, which are a cast-in-place construction type. Their concrete label is C35, and the pile embedded length is 36 m in the dense sand layer.

3. Resonance compaction treatment

To ensure the safety of the foundation and to reduce costs, the RCM with a self-developed cross-wing was used to reinforce the natural foundation. The mechanism of the cross-wing compaction method for liquefaction soil treatment is a reduction in the soil volume (compaction), an increase in the sand density (modulus) and a permanent preconsolidation effect (Massarsch and Fellenius, 2014). In this process, a vibratory hammer transmits energy to the surrounding soil through an oscillating probe that produces vibrations along with compression waves, shear waves, and Rayleigh waves. This first results in the destruction of soil structures and decreasing friction along the probe. As the vibration continues, the excess pore water pressure dissipates, effective stress increases and the friction between the probe surface and the surrounding soil again increases along the probe.

In this study, a 20 × 50 m test site was chosen and reinforced using

Table 1
Geotechnical properties of the soil layers at the test site.

Soil layers	Average thickness	Unit weight	Void ratio	Plastic index	Liquidity index	Compression modulus	Poisson's ratio	Internal friction angle	Cohesion
	d (m)	γ (kN/m^3)	e	I_P	I_L	M (MPa)	ν	φ (°)	c (kPa)
Silt	7	18.3	0.83	8.3	1.2	7.1	0.35	30.1	9.0
Silty sand	4	18.2	0.84	–	–	7.9	0.30	33.6	8.3
Clay	4	18.8	0.87	17.5	0.8	4.2	0.45	12.7	20.0