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Performance of X-shaped and circular pile-improved ground subject to liquefaction-induced lateral spreading

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ABSTRACT

Liquefaction-induced lateral spreading has caused severe damage and significant financial losses in major earthquakes distributed globally. Groups of piling installed in liquefaction- and lateral spreading-susceptible ground has been proven to be effective in reducing lateral displacements, but further investigation into the soil-structure interactions is required to elucidate the mechanisms for mitigation of displacement. Further, it is hypothesized that cross-, or X-shaped, piling may provide improved restraint on lateral flow deformations due the destructive interference of flow imposed by their cross-section. In this paper, the effectiveness of groups of X-shaped and circular piles to mitigate lateral spreading ground was investigated to improve the understanding of the mechanisms for improvement. Shake table tests were carried out to examine and compare the efficacy and efficiency of X-shaped and circular pile groups. Design parameters including the pile arrangement (square vs. triangular spacing) and orientation (X vs. +) of the X-shaped piling were also taken into consideration. The results demonstrate that the X-shaped pile groups can significantly reduce the lateral displacement and the areal extent of liquefied sand flow as compared to the unimproved and circular pile-improved ground, and that the spacing and orientation play a critical role in the deformation response. These findings will help inform the design of pile-improved ground as well as the design of structural piling adjacent to submerged, liquefiable slopes.

1. Introduction

Lateral spreading is a common consequence of liquefaction of gently-sloping crustal soils or soils adajacent to free faces, and may produce significant damage to adjacent structures. Saturated, liquefaction-susceptible deposits under existing shear stresses and subjected to seismic excitation tend to produce large lateral displacements, characterized by compressional features at the toe, shearing along the sides, and extensional features at the head scarp of the spreading mass and can extend to large distances [1]. Large, liquefaction-induced ground displacements have caused severe damage to port and harbor facilities, bridge and structure foundations, lifeline facilities, and other infrastructure [2–6].

Significant effort to mitigate the effects of liquefaction have been developed since the mid-1960s, when the significance of the effects of liquefaction was generally first recognized [7]. Ground improvement methods developed since aim to provide densification, reinforcement, drainage, or some combination of these improvement mechanisms. Densification may be achieved through shallow or deep dynamic compaction [8], compaction grouting [9], vibro-compaction [10], explosive compaction [11], or driven [12,13] or drilled [14] displacement piling. Reinforcement techniques include deep soil mixing [15] and pile-pinning, whereas drainage measures have been considered with vibro-replacement and –displacement [16] and pre-fabricated vertical drains [17,18]. Depending on the targeted level of mitigation of deformations, traditional ground improvement methods have been applied to limit residual shaking-induced excess pore pressure to less than 100% of the initial vertical effective overburden stress and the development of unrestrained lateral flow. Application of countermeasures against significant lateral spreading is ideal, but is also expensive and time-consuming. With the advance of performance-based design concepts in earthquake engineering [19], it is commonly more cost-effective to allow for the onset of initial liquefaction while preventing the significant deformation and associated damage.

In this regard, several researchers have investigated different countermeasures to reduce the permanent displacement that can develop from lateral spreading. Yasuda et al. [20] conducted a series of shake table tests to study four types of countermeasures against liquefaction-induced lateral spreading, including sand compaction piles, steel piles, a continuous densified granular panel, and a continuous

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underground structural wall. Iai [21] summarized remedial measures used for port structures and provided case histories of implementation and performance of these measures during earthquakes. Motamed and Towhata [22] evaluated three remedial techniques for improving the seismic performance of pile groups and quay walls. The study revealed the importance of pile fixity on restraining soil movement behind quay walls and the associated bending moments in the retained pile groups. Takahashi et al. [23] verified the efficacy of pile-type improvement against large displacements of liquefied ground using centrifuge model tests and investigated the optimization of pile arrangement with a view to cost-effectiveness. In these and other experiments, it may be observed that the installation of piling for the mitigation of liquefaction-induced deformations is similar to instances where piles that were not intended for mitigation were also subject to the lateral flow associated with liquefaction. Thus, lessons learned from numerous studies [24–29] that have been conducted to study the response of piles embedded in liquefied ground can be applied to pile mitigation strategies. However, these studies focused mainly on the performance of the piles. The physical mechanisms and resulting patterns of lateral flow and displacement around piling, and strategies to alter the soil-pile interaction and disrupt lateral flow requires further research.

This study presents an experimental shake table test program conducted to evaluate a new type of pile shape developed to reduce liquefaction-induced lateral spreading-type displacement. The new pile type is termed the X-shaped cast-in-place concrete (XCC) pile and is shown in Fig. 1. The pile is installed using a hollow, X-shaped mandrel with a pyramidal, moveable flap that is vibrated to depths of up to 25 m prior to being withdrawn as concrete is pumped through the mandrel. The X-shape section creates a larger perimeter than a circular pile with the same cross-section area. Therefore, compared with the conventional circular pile, the XCC pile can increase pile shaft resistance for structural support while reducing the volume of concrete necessary to form the section. The XCC pile has been widely used in China for ground improvement [30,31] and structural support [32–35], but its effectiveness to restrain lateral spread-type movements has not yet been sufficiently studied. Assuming the flow of liquefied ground to be fluid-like, the special X-shape section could be more effective in restricting lateral flow of liquefied soil than conventional circular sections. The experimental program conducted to evaluate the efficacy and efficiency of the XCC pile to mitigate the lateral spreading of liquefied ground is described and includes a comparison of performance against the conventional circular pile type. The parameters investigated include the pile arrangement (square vs. triangular spacing) and the orientation (X vs. +) of the XCC pile in plan to observe their effect on the magnitude and extent of flow-type movements. Measurements of excess pore pressure generation, propagation of ground motions, and lateral displacements of the piles and surrounding soil are used to compare performance across the variables investigated. This study shows that the X-shape section does indeed reduce flow-type movements relative to circular sections, and that the orientation of the X-shape can reduce the flow of liquefied soil. The results of this study can guide future use of XCC piles in liquefaction- and lateral spread-susceptible soils and soil profiles.

2. Shake table tests

Shake table tests have served as the basis for numerous experiments on pile-improved ground [36–40]. The experimental evaluations of the XCC piles were conducted using the shake table facility at Chongqing University. The shake table is capable of moving in horizontal and vertical direction simultaneously, with a maximum base excitation and frequency of 2 g and 50 Hz, respectively. A rigid soil container with geometry of 950 mm in length, 850 mm in width, and 550 mm in depth was used in the shake table tests reported herein (Fig. 2). Two approaches were used to reduce the reflection of energy associated with rigid boundary conditions: first, relatively compressible foam cushions were placed at the front and back of the container in the direction of shaking; then, the slope near the front boundary was steepened as described in greater detail below. Experiments were conducted using a sinusoidal base excitation with an amplitude of 0.2 g and a frequency of 5 Hz over a duration of 10 s. The base excitation was applied in the longitudinal direction, parallel to the direction of the model slope.

2.1. General components of the physical models

Fig. 2 shows the schematic plan and elevation view of

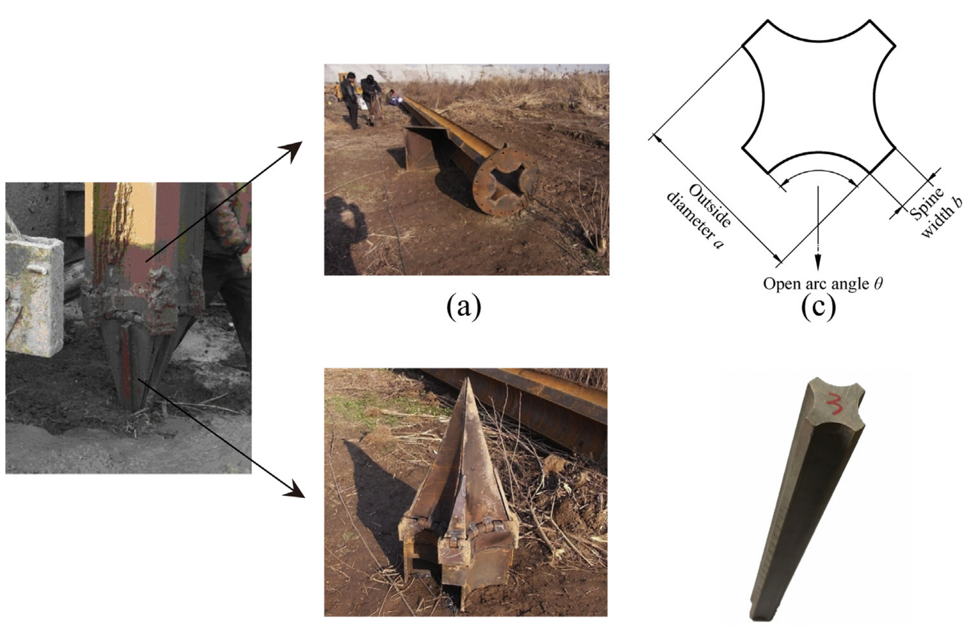

Fig. 1. Photographs showing the (a) X-shaped section of the pile mold used to form the XCC pile, (b) the conical shoe with X-shaped cross-section fitted to the pile toe for installation, (c) the geometrical dimensions used to specify the XCC pile, and (d) 3D printed model pile used in the shake table experiments.