Use of bag-sealed bored pile in Karst areas

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ABSTRACT

Casting bored piles in Karst areas is often problematic, since the concrete can penetrate through cave systems or underground stream channels, resulting in poor construction quality of bored piles with insufficient bearing capacity. A new type of bored pile is proposed to cast the concrete within a rubber/geotextile bag in the bored hole, which can restrict the loss of concrete through stream channels in Karst areas. In this study, model-scale laboratory tests were conducted to assess the feasibility of casting rubber/geotextile bag-sealed bored pile and to evaluate its bearing behavior. The measured results for a bag-sealed pile within Karst regions and a normal pile with equal diameter in a uniform ground without stream channels were compared. It demonstrates that casting bored pile within a big is an effective solution to increase the bearing capacity of pile under static loads. The ultimate bearing capacity of bag-sealed pile is about 1.5 times that of equal-diameter pile. The settlement of bag-sealed pile is much smaller than that obtained for equal-diameter pile under the same loading conditions.

Key words: Karst area, bag-sealed pile, bearing capacity, settlement

1 INTRODUCTION

Karsts are widely distributed in China, especially in the Southwest region, representing a severe type of engineering geological hazards. In recent years, a large number of high-rise buildings, bridges and other infrastructure have been built in Karst areas. Due to the high demand in bearing capacity, bored pile is extensively used in Karst areas because of its good adaptability to the site. However, there are many problems associated with casting bored piles in Karst areas in practice: (a) the concrete can penetrate through stream channels easily. Without a proper control of the concrete, the stability of bored hole becomes hard to maintain during the casting process, or it leads to difficulty in drilling. (Shi et al., 2015; Xiong et al., 2018); (b) the Karst development affects the quality and the bearing capacity of bored pile significantly, endangering design of superstructures (Jin et al., 2005; Wong et al., 2011).

At present, research on pile foundation in Karst areas mainly focused on the mechanical characteristics and the stability analysis of the Karst cave roof. For example, Zhao et al. (2018) and Cao et al. (2013) considered the overall bearing effect of the roof with different strength theories in their calculation model for pile tip resistance. Zhang et al. (2013a, 2013b) studied the importance of different influencing factors in the determination of bearing capacity for pile foundation in Karst areas through a series of model-scale experiments, and found that the bearing capacity of pile was closely related to the geometric correlation between the pile and the Karst cave, the strength characteristics of the surrounding rock, and the thickness of the Karst cave roof. Pells et al. (1979) proposed an analytical model to calculate the rock-socketed depth of bridge pile foundation in Karst areas. However, there are limited studies on modification of cross-section of bored pile in Karst areas.

In view of the lack of investigations on improving the bearing behavior of bored pile in Karst regions, a new type of bored pile is proposed to cast the concrete in a rubber/geotextile bag within the bored hole, inspired by the use of helical pile (Naggar et al., 1999; Fahmy et al., 2016) and the geotextile bag injection method in grouting applications (Guo et al., 2012). A bag-sealed bored pile can simulate the contribution from branched sections following the characteristics of natural cavity, (i.e. Karst cave and soil cave) in Karst areas. Based on conventional bored pile techniques, a flexible rubber/geotextile bag is set to wrap around the poured concrete, such that the loss of concrete through stream channels cannot occur. Due to the applied grouting pressure, the bag is squeezed into the cavern during the casting process to form branched sections.
as schematically shown in Fig. 1 (Mei et al., 2016). In this paper, the use of flexible rubber/geotextile bag was tested to evaluate whether bag-sealed bored pile can be cast in Karst areas. A further static load test was set to measure bearing capacity and deformation performance of bag-sealed and normal piles to illustrate the benefits of casting branched sections.

2 LABORATORY EXPERIMENTS

2.1 Assumptions

In this study, two series of model-scale laboratory tests were carried out, where the performance of an equal-diameter pile was compared against behavior of a bag-sealed pile with the same diameter. In this preliminary testing program, only few key factors, including the geometric characteristics of pile and the physical and mechanical parameters of bedrock, were considered to assess their influence on the bearing capacity and settlement response of piles (Randolph, 2003). The following assumptions were made: (a) the bedrock was a uniform medium with a horizontal ground surface; (b) the influence of groundwater was neglected, and as such all connected stream channels were empty; (c) all connected caverns were only distributed horizontally around the pile.

2.2 Test chamber

The first test series was carried out to demonstrate the casting procedure for bag-sealed bored pile. A model box was manufactured to have dimensions of 200 mm × 200 mm × 600 mm as depicted in Fig. 2. The model container can be split in half, and bedrock materials were poured in each half to form stream channels. The two halves were mounted together, in which a rubber bag can be dragged down in position. Cement mortar was then cast to form in situ bag-sealed bored pile. The bored pile has a length of 500 mm and a diameter of 60 mm. It should be emphasized that the size of the rubber bag was slightly larger than the size of the pile body. In this way, branched sections can be formed easily, once the bag was expanded at the positions of stream channels upon the applied grouting pressure.

Static load test series were performed on manufactured model piles. The model container was made to have dimensions of 600 mm × 600 mm × 800 mm. A normal pile was made of steel tube with a length of \( L = 600 \text{ mm} \) and a diameter of \( D = 30 \text{ mm} \). A bag-sealed bored pile was also manufactured with steel, and branched sections were welded directly. A layer of latex film was then wrapped around the pile with branches to simulate the interface behavior between bedrock and bag. The normal pile and the bag-sealed bored pile had the same diameter. It should be noted that the size of the model box was 20 times larger than the pile diameter, and the distance between the pile tip and the bottom of the model box was 6 times the pile diameter. The boundary effect was considered to be negligible. Before pouring bedrock materials, all sidewalls of the model box was coated with Vaseline and a layer of polyethylene film to further eliminate the boundary effect. The schematic diagram of model piles are illustrated in Fig. 3.

2.3 Materials

The bedrock was made of gypsum due to the similarity in mechanical properties between gypsum and Karst foundation (Lin, 1984). It is convenient to cast the Karst caverns and stream channels in gypsum because of its relatively small hardness. In the test, the ratio between gypsum and water was controlled as 1.5:1. As shown in Fig. 2, the irregular distribution of Karst caverns in the foundation model can better reflect the prototype behavior of foundation.

The established similitude laws were adopted to model the problem. The similarity ratio between model- and prototype-scale behavior was taken as \( C_l = 16 \) and \( C_p = 1.2 \), for geometry and density, respectively. The similarity ratio for other parameters was obtained following the similarity theory as: stress of \( C_{\sigma} = 19.2 \), elastic modulus of \( C_{E} = 19.2 \), cohesion of \( C_c = 19.2 \), and internal friction angle of \( C_{\varphi} = 1 \).
Therefore, the required range of physical and mechanical parameters of simulated bedrock was determined as follows: density of 1.91~2.34 kg/m$^3$, compressive strength of 1.6~6.5 MPa, elastic modulus of 0.1~0.42 × 10$^4$ MPa, cohesion of 0.17~0.33 MPa, internal friction angle of 30°~44.6°. The bedrock in the prototype-scale was limestone. Referring to the previous research (Zuo et al., 2004), sand, cement and gypsum mixtures (the weight ratio between medium sand, cement, and gypsum was defined as 6:0.7:0.3) were used to form bedrock materials in the experiment. According to the relevant literature (Liu et al., 2005), the physical and mechanical parameters of limestone were statistically analyzed, the generalized parameters of the mixture were defined as summarized in Table 1.

<table>
<thead>
<tr>
<th>Generalized parameters</th>
<th>Limestone</th>
<th>Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg·m$^{-3}$)</td>
<td>2.3~2.8</td>
<td>2.04</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>32~125</td>
<td>2.1</td>
</tr>
<tr>
<td>Elastic modulus ($10^4$ MPa)</td>
<td>1.8~8</td>
<td>0.24</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>3.3~6.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>30~44.6</td>
<td>40.3</td>
</tr>
</tbody>
</table>

The flexible rubber bag was made of latex film with a diameter of 66 mm, a length of 510 mm, and a thickness of 0.3 mm. The elastic modulus of latex film was $E=0.014$ GPa and the poisson’s ratio was $\nu=0.45$.

2.4 Instrumentation and data analysis

The measuring system consists of the following parts: (a) a pair of dial gauges were mounted symmetrically above the pile head to measure the settlement; (b) a load cell with an accuracy of 0.01 kN was placed on the pile head to read the applied force.

2.5 Testing program

In the first test series, the casting process between normal (equal-diameter) and bag-sealed bored piles is compared. The curing period for both piles was set as 3 days. In the second test series, the model pile was fixed in position, around which the bedrock materials were poured in layers. Once the bedrock reached a target depth, the earth pressure cell was installed. Pouring was continued until it reached the ground surface, and the model pile was kept vertically during the whole process. The loading system and the measurement system were assembled after the foundation rock was cured for seven days. The test setup is illustrated in Fig. 4. The model pile was loaded in stages with a load increment of 0.5 kN.
3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Casting test of bag-sealed bored pile

After 3 curing days, the bag-sealed bored pile is shown in Fig. 5, from which it can be seen that the Karst foundation remains intact. The main pile body is cast vertically, and there is no damage in the pile (e.g. necking pile, short pile and broken pile). Branched sections are formed clearly within the latex film following the Karst caverns without the presence of slurry leakage. It should be noted that the formation of branched sections becomes less obvious when the size of the Karst caverns decreases. It is observed that, in principle, the length of branched sections increases with the radius of the cavern, which is about one half of the height of the Karst cavern. The formed branched section has a hemispherical shape. Due to the grouting pressure, branched sections are in close contact with surrounding bedrock. It demonstrates that the use of flexible rubber/geotextile bag is effective to cast bag-sealed bored and prevent the loss of cement mortar during the cast process.

Fig. 5. Photo of bag-sealed bored pile with branched sections.

3.2 Bearing capacity and deformation behavior of bag-sealed bored pile

The $Q$-$s$ curves measured for equal-diameter and bag-sealed bored piles are depicted in Fig. 6. In the equal-diameter pile test, there is a sharp drop of settlement once the applied load exceeds 3 kN, which is determined as the ultimate bearing capacity following the design code. In the bag-sealed bored pile test, the $Q$-$s$ curve shows a drop of settlement after a load level of 4.5 kN, which is 1.5 times larger than the value for the normal pile. It confirms that the branched sections for bag-sealed bored pile can improve the bearing capacity compared to an equal-diameter pile greatly, but the increase in the total volume of grouting is less than 10%.

Fig. 6. Comparison of the measured $Q$-$s$ curves between equal-diameter and bag-sealed bored piles.

It can be seen from Fig. 6 that the settlement at the pile head for bag-sealed pile is very small at the initial loading stage. When the applied load reaches 1.5 kN, the settlement for equal-diameter pile is 0.52 mm, while the settlement for bag-sealed pile is less than 0.1 mm. This indicates that the branched sections of bag-sealed bored pile can contribute to the skin friction of the pile. With the increase of load, the settlement for equal-diameter pile increases much faster than that for bag-sealed pile. For equal-diameter pile, at the ultimate bearing capacity of 3 kN, the settlement at the pile head is about 0.89 mm; whereas the settlement for bag-sealed bored pile is 0.51 mm, being only 57% of the former. For bag-sealed bored pile, when the ultimate load of 4.5 kN is reached, the measured settlement is only 0.86 mm. For bag-sealed bored pile, the branched sections can contribute to provide skin friction, since a greater range of the surrounding rock is mobilized.

4 CONCLUSIONS

In this paper, a new type of bag-sealed bored pile is proposed to cast concrete piles in Karst areas. The feasibility in the casting procedure of bag-sealed bored is evaluated, and the bearing capacity and deformation performance of bag-sealed bored pile are also investigated through laboratory tests. The main conclusions from this work are drawn as follows:

(1) The flexible rubber/geotextile bag (i.e. latex film) can wrap the concrete during the casting process of bored pile, and minimize the loss of slurry effectively compared to an ordinary equal-diameter pile. The formation of branched sections can improve the contact between the pile and the surrounding rock, improving the bearing capacity of bag-sealed pile.

(2) The ultimate bearing capacity of bag-sealed bored pile is much larger than that of equal-diameter pile by approximately 1.5 times, but
the difference in volume of concrete between the two piles is not much. This shows the significant economic benefit of casting bag-sealed bored pile. The settlement of bag-sealed pile is much smaller than that of equal-diameter pile under the same loading conditions. Bag-sealed bored pile is an ideal alternative for structures in Karst areas to increase the bearing capacity and minimize the settlement.

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