The Comparative Study of Single Pile Bearing Characteristics in Calcareous Sands Foundation and Quartz Sands Foundation Based on Model Experiment

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Abstract. The bearing characteristics of single steel pipe pile in calcareous sands foundation and quartz sands foundation with different relative compactness are compared and analyzed by the model tests of single steel pipe pile in two kinds of soil media in laboratory. The test results show that the bearing behavior of single steel pipe pile is quite different between calcareous sands and quartz sands. Pile end forms of single steel pipe pile have little influence on the bearing capacity, especially in the sands foundation with high relative compactness. Increasing the relative compactness of foundation soil has obvious effect on improving the bearing capacity of single steel pipe pile. But the bearing capacity of single steel pipe pile in calcareous sands is much lower than that in quartz sands in the same relative compactness. The lateral friction resistance of single steel pipe pile in quartz sands is much larger than that of calcareous sands. The lateral friction resistance of single steel pipe pile in calcareous sands does not increase significantly with the increase of relative compactness; But the lateral friction resistance of single steel pipe pile in quartz sands increases significantly with the increase of relative compactness. In calcareous sands foundation, the ratio of load sharing on the side of single steel pipe pile is small, and the load on the pile top is mainly borne by the soil at the pile end, and it is manifested as friction end bearing pile. In the quartz sands foundation, the axial force of the pile decreases rapidly along the pile. And the faster the axial force of the single pile of the steel pipe is decayed with the smaller compactness of the quartz sands.

1. Introduction
Calcareous sands are geotechnical medium of marine biogenic. They are the kind of CaCO₃ content more than 50% of the granular, sheet materials. They have the low particle strength, irregular shape, sharp edges and corners, and inside pores etc. So they are easy to grain breakage (WANG Ren et al., 1997; Liu Chongquan et al., 1995). There are special properties of calcareous sands. So that make the pile bearing properties extremely complex in such foundation. And the traditional experience is difficult to apply in the pile foundation engineering in calcareous sands strata (ALBA J L and AUDIBERT J M, 1999; NYLAND G, 1988; RAINES R D et al., 1988; DUTT R N and INGRAM W B, 1991). Indoor model tests and field tests of pile bearing performance for calcareous sands foundation were studied widely by scholars (SHAN Huagang, 2000; JANG Hao, 2009, 2010; QIN Yue et al., 2014, 2015). The study on bearing properties of pile foundation in calcareous sands strata is particularly important especially in recent years for oil and gas resources exploration and exploitation,
and development of the south China sea islands and the need of national defense. In this paper, the properties of single pile bearing in calcareous sands foundation were studied. It analyzed the relationship of load-settle and axial force transfer characteristics of single pile and side friction characteristics. End-open single steel pipe pile and end-closed single steel pipe pile were compared both in calcareous sands foundation and quartz sands foundation.

2. Test Materials and Test Methods

2.1. Testing Materials
The testing calcareous sands were taken from a reef, where is near the Nansha waters of the south China sea. They are loose coral clastic sediments. And tests contrast materials were quartz sands. Moisture contents of calcareous sands and quartz sands were less than 2%. It was controlled relative density of 46% and 75% by layered and loaded lightly of calcareous sands and quartz sands to reduce the effect of particle breakage on test results. Physical property parameters and particle size distributions curve of test material are shown in table 1 and figure 1.

Table 1. Physico-mechanical properties of soils

| Testing materials | Coefficient of Uniformity $C_u$ | Coefficient of Curvature $C_c$ | Specific Gravity $G$ | Maximum Void Ratio $e_{max}$ | Minimum Void Ratio $e_{min}$ |
|-------------------|---------------------------------|-------------------------------|----------------------|-----------------------------|-------------------------------|
| Calcareous Sands  | 2.78                            | 1.19                          | 2.8                  | 1.48                        | 1.00                          |
| Quartz Sands      | -                               | -                             | 2.65                 | 0.97                        | 0.52                          |

Figure 1. Particle size distributions of calcareous sands and quartz sands.

2.2. Testing Scheme
Test model box was a rigid cylinder, whose diameter was 700 mm; and height was 900 mm. Model pile was seamless steel tube, whose elastic modulus was $2.06\times10^5$MPa; and outside diameter was 30 mm; and inside diameter was 24 mm; and length was 600 mm.

Geometric similarity ratio was 1:30 in this tests (YANG Junjie, 2005). Jiang Hao (Jiang Hao, 2009) researched the boundary effect by measuring soil pressure in sands box test model of near the walls and the bottom of each embedding; the test results showed that the soil force was very little, that can be negligible; and it could be thought of as the boundary effect eliminated. And according to the similarity theory (YANG Junjie, 2005), it did not have to worry about the boundary effect of this
model box. Testing loading which was used 3 kN hydraulic jack, was controlled by the oil pressure gauge. And testing was rapid loading. Per level was loading 1 hour, then it could start the next level loading. Testing data were recorded in 5, 15, 30, 45, 60 minutes. The testing could be terminated if the settlement of pile top was as 5 times as the settlement of previous loading or reach jack range. Two dial indicators were set at symmetric pile head to measure displacement of pile top. Five strain measuring point were distributed averagely in the pile body. Test components were used foil type resistance strain gauge, which was special moisture-proof. And temperature compensations were set in the soil close to the model box. That must be calibrated all the measurement sensor before the tests.

3. Testing analysis

3.1. Influence on Load-bearing Characteristics of Pile End Forms for Single Steel Pipe Pile

Figure 2 shows the relationships of load and settlement curves on the pile top for end-open single steel pipe pile and end-closed single steel pipe pile in different compactness foundations. When the pile top load is light, the relationship between load and settlement on the pile top in calcareous sands foundation was linear due to the elastic phase of the soil around the pile in the calcareous sand foundation. End-open single steel pipe pile and end-closed single steel pipe pile of Q-s curves were similar in calcareous sands foundation; and pile end form of single steel pipe pile had little impact on the bearing capacity. But compactness of calcareous sands foundation effected significantly on bearing capacity of single steel pipe pile. When pile top load continued to increase, pile periphery soils transitioned from elastic stage to elastic-plastic stage; So that the relationships of load and settlement on the pile top were nonlinear. The soils were squeeze into the end-open single steel pipe pile to form a soil plug effect, which increases the bearing capacity of the single steel pipe pile. When the calcareous sands foundation compaction (Dr) is increased from 46% to 75%, single pile limit bearing capacity of end-closed single steel pipe pile increases from about 12% to about 17% more than that of the end-opened single steel pipe pile. Bearing capacity of single steel pipe pile in calcareous sands foundation was lower than that in quartz sands foundation of the same compactness. For example, when the foundation compactness (Dr) was 75%, single pile limit bearing capacity of single steel pipe pile that was 2.15 kN in calcareous sands foundation; that was about 66% of single pile limit bearing capacity (1.42 kN) in quartz sands foundation.

![Figure 2. Q-s curves of end-open pipe pile and end-closed pipe pile.](image)

3.2. Characteristics of Axial Force for End-closed Single Steel Pipe Pile

Figure 3 shows pile axial force curves of end-closed single steel pipe pile both in quartz sands foundation and calcareous sands foundation in different compactness foundations. In calcareous sands foundation, undertaking load was less in pile periphery soils; and most of the load was borne by the pile endpoint soils. The pile endpoint soils undertook for more than 70% of loading. It was friction end bearing pile trait. And the greater the compactness of the limestone sand foundation, the greater the
load on the soil at the pile end. For example, when the calcareous sands foundation compactness (Dr) was 75%, the load sharing ratio of pile end soil increased about 5% more than that of 46% compactness (Dr) calcareous sands foundation. (Figure 4)

![Graphs showing load sharing ratio vs. depth for different loading and compactness levels.](image)

**Figure 3.** Axial force of end-closed single steel pipe pile.

There was shown a great difference of pile axial force distribution characteristics between quartz sands foundation and calcareous sands foundation in Figure 5. In quartz sands foundation, the pile axial force reduced rapidly with the depth; and axial force attenuation rate was increases with increasing depth; And the load sharing ratio on pile-end soils was increase quickly with the increase of loading; and the foundation was denser; the load sharing ratio was much larger on pile-end soils. For example, when the loading was 0.22 kN in 46% compactness calcareous sands foundation, the load sharing ratio was about 5% on pile end soils; and when the loading was 0.95 kN, the load sharing ratio was about 46% on pile end soils; and when the loading was 0.34 kN in 75% compactness calcareous sands foundation, the load sharing ratio was about 12% on pile-end soils; and when the loading was 2.90 kN, the load sharing ratio was about 70% on pile-end soils. Compared with the calcareous sands foundation, the load sharing ratio on pile end soils was higher in calcareous sands foundation than that in quartz sands foundation. The load sharing ratio on pile end soils was a little difference in calcareous sands foundation, but the difference was not very in all of the calcareous sands foundation; It was about 68%~86%, such as table 2.
Figure 4. Axial force of end-closed single steel pipe pile in different compactness of calcareous sands.

Figure 5. Axial force difference of end-closed single steel pipe pile in calcareous sands foundation.

Table 2. Load sharing ratio of soils at pile end.

| Foundation Soil | Compactness Dr(%) | Loading on pile top (kN) | Pile tip loading (kN) | Loading proportion of pile tip (%) |
|-----------------|-------------------|--------------------------|-----------------------|----------------------------------|
| Calcareous Sands | 46 | 0.22 | 0.15 | 68 |
|                 | 75 | 0.34 | 0.25 | 74 |
| Quartz Sands    | 46 | 0.95 | 0.44 | 46 |
|                 | 75 | 0.34 | 0.04 | 12 |

3.3. Characteristics of Pile Lateral Friction of End-closed Single Steel Pipe Pile

The friction forces of end-closed single steel pipe pile are showed in Figure 6. It showed that pile lateral friction distributions were similar both in calcareous sands foundation and quartz sands foundation. And it was nearly parabolic distribution form. Pile lateral friction increased with the pile top load both in calcareous sands foundation and quartz sands foundation. When the pile top load exceeded a certain value, the pile lateral friction was maintain a stable range rather than changed greatly with the increase of load.

We should note that pile lateral friction did not obviously increased with compactness in the calcareous sands foundation. When compactness(Dr) were 46% and 75% for calcareous sands foundation, pile side limit friction resistances were 3.86 kN and 4.56 kN. But pile side limit friction resistance was an obvious increase with compactness in the quartz sands foundation. When the foundation compactness(Dr) were 46% and 75% for quartz sands foundation, pile side limit friction resistances were 14.08 kN and 22.84 kN. The same conclusion can be drawn from Table 2. The increase of pile top load and the increase of relative density have not changed the bearing characteristics of single steel pipe in calcareous sand foundation, and it always appears as friction end pile. In the quartz sand foundation, when the pile top load is low, the pile lateral friction has beared most of the load. With the increase of the compactness, the single pile bearing characteristics of single steel pipe pile changed from the end bearing friction pile to the friction end pile.
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Figure 6. Friction force of end-closed single steel pipe pile.

It is generally believed that the friction angle of calcareous sands is larger than that of quartz sands (DATTA M et al.; 1979). But pile lateral friction of steel pipe pile in calcareous sands foundation was much less than that in quartz sands foundation. This was caused by calcareous sands particle breakage. Pile lateral friction can be determined by the math.

\[
q_i = \sigma_a \tan \delta = K \sigma_v \tan \delta
\]  

(1)

In the math, \(\sigma_a\) is the horizontal soil effective stress on the pile side; \(\sigma_v\) is the vertical soil effective stress; \(K\) is coefficient of static earth pressure; \(\delta\) is frictional angle of the pile-soil interface.

When the pile top was been loading, soils would be sheared and compressed by the pile-soil stress transfer at the same time. When calcareous sands were sheared, there would be a lot of particle breakage. Squeezing made the soils compaction, but it prompted the calcareous sands particle breakage at the same time. So that it changed calcareous sands gradation; and pile horizontal effective stress was decreased. The particle breakage lead to effective stress decrease that was much more than that increased by compacting effect in calcareous sands foundation.

4. Conclusion

The bearing behavior of single steel pipe pile is quite different between calcareous sands and quartz sands. Pile end forms of single steel pipe pile have little influence on the bearing capacity, especially in the sands foundation with high relative compactness. Increasing the relative compactness of foundation soil has obvious effect on improving the bearing capacity of single steel pipe pile. But the bearing capacity of single steel pipe pile in calcareous sands is much lower than that in quartz sands in the same relative compactness. The lateral friction resistance of single steel pipe pile in quartz sands is much larger than that of calcareous sands. The lateral friction resistance of single steel pipe pile in calcareous sands does not increase significantly with the increase of relative compactness; But the
lateral friction resistance of single steel pipe pile in quartz sands increases significantly with the increase of relative compactness. In calcareous sands foundation, the ratio of load sharing on the side of single steel pipe pile is small, and the load on the pile top is mainly borne by the soil at the pile end, and it is manifested as friction end bearing pile. In the quartz sands foundation, the axial force of the pile decreases rapidly along the pile. And the faster the axial force of the single pile of the steel pipe is decayed with the smaller compactness of the quartz sands. In the quartz sand foundation, when the pile top load is low, the pile lateral friction has beared most of the load. With the increase of the compactness, the single pile bearing characteristics of single steel pipe pile changed from the end bearing friction pile to the friction end pile.

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