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# Lateral characteristics of rigid piles under large displacement

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**Abstract**. Based on the model test data and the numerical simulation method, the characteristics of rigid piles under large displacement are studied in this paper. The results show that the bending moment of the pile has a linear growth in the cantilever segment, when the distance from the top of the pile is greater than 0.7m, the increasing trend of the pile's bending moment gradually slows down, the bending moment of the pile becomes the maximum when the distance from the top of the pile is 1.1m, and the bending moment tending to 0 near the bottom of pile. In the case of large displacement, the soil in front of the pile shows obvious plastic yielding, and the soil resistance of the pile is no longer linearly increased with the increase of load.

## 1. Introduction

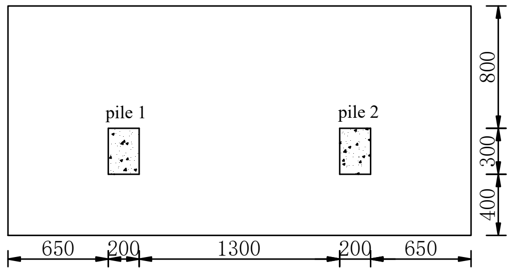
Pile is widely used in geotechnical engineering, such as rectangle anti-slide pile, pier, building and Port Pile Foundation in landslide treatment. A lot of analysis has been done about lateral characteristics of rigid piles [1~6]. However, there is little research on the lateral characteristics of rigid piles under large displacement. The current norms of construction and bridge Pile Foundation only allow a small amount of horizontal displacement of the pile, but in fact, there is no strict restriction on the horizontal displacement of pile for the anti-slide piles in slope treatment, the pile-type retaining wall in subgrade filling and the Port Pile Foundation.

Cui Xz and others [7~10] through model test, theoretical deduction, numerical simulation and other means, analyze the failure modes, displacement regularity and ultimate bearing capacity of rigid piles under lateral load. There is little research on the failure mode and elastic-plastic characteristics of the lateral soil of rigid piles under large displacement.

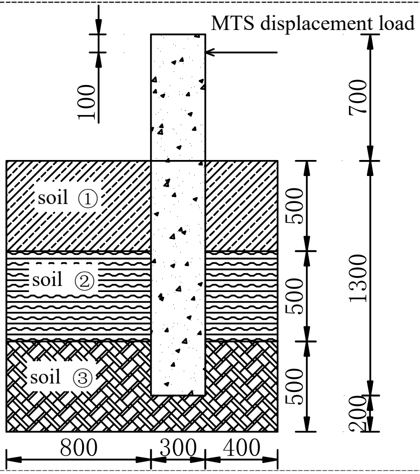
In view of this, this paper studies the failure mode and elastic-plastic characteristics of rigid piles under lateral load based on indoor model test and numerical simulation.

## 2. Model establishment and parameter selection

In this paper, 1/10 Indoor physical model test is carried out [11]. The displacement load is applied simultaneously to the retaining (pile 1), non-retaining (pile 2) of rigid pile. The clay in the model box is made up of three layers of compacted loess, and the thickness of each layer is 500mm. The specific scheme is shown in Figure 1 (mm in the figure), detailed parameters of the soil are shown in table 1.




(a) model box plan drawing



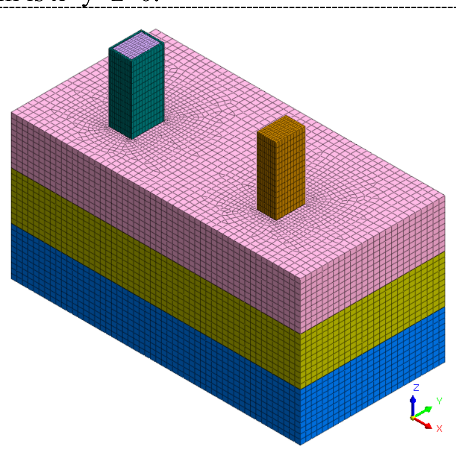

(b) model box elevation drawing

Figure 1. Schematic diagram of the model scheme

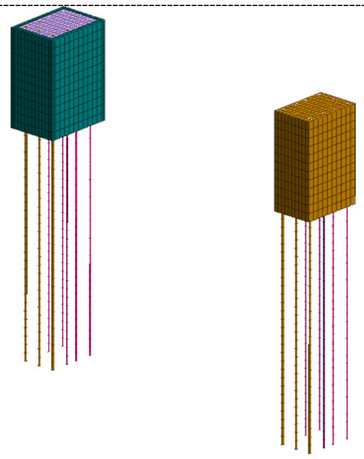
Table 1. Model material parameters

| material | moisture content ω (%) | severe γ (kN·m$^{-3}$) | cohesive force (kPa) | angle of internal friction ψ (°) | compression modulus $E_s$ (MPa) | | modulus of elasticity E (MPa) |
|---|---|---|---|---|---|---|---|
| | | | | | $E_{s1-2}$ | $E_{s2-3}$ | |
| soil① | 19.1 | 19.7 | 15 | 5.6 | 5.31 | 8.89 | |
| soil② | 17.3 | 19.8 | 8.5 | 5.8 | 5.98 | 9.94 | |
| soil③ | 22.2 | 20.8 | 9.0 | 4.9 | 6.54 | 9.72 | |
| concrete (C15) | | 25 | | | | | 18300 |
| reinforcement (HRB400) | | 78 | | | | | 200000 |

Based on the above model test, this paper will use the finite element software Midas GTS NX to establish a three-dimensional solid numerical calculation model, as shown in Figure 2. The pile and soil are all used 3D solid element, the reinforcement adopts the 1D implanted beam element. The side of the model is constrained by normal displacement (front and rear y=0, left and right x=0), and the bottom is x=y=z=0.



(a) Model overall grid diagram



(b) Reinforcement grid diagram

Figure 2. Numerical model grid diagram

The soil adopts the molar-Coulomb constitutive, the concrete adopts the elastic constitutive, the reinforcing bar adopts the elastic constitutive, the concrete parameters are shown in table 2.

Table 2. Material parameters for numerical simulation

| soil | severe γ (kN·m$^{-3}$) | cohesive force c (kPa) | angle of internal friction ψ (°) | compression modulus $E_s$ (MPa) | modulus of elasticity E (MPa) |
|---|---|---|---|---|---|
| soil① | 19.7 | 15 | 14 | 9 | - |
| soil② | 19.8 | 16 | 15 | 9 | - |
| soil③ | 20.8 | 16 | 16 | 10 | - |
| concrete | 25 | - | - | | 18300 |
| reinforcement | 78 | | | | 200000 |

## 3. Model validation

In order to verify the reliability of the numerical model, the load-displacement curve of numerical simulation and the model test are compared, as shown in Figure 3.

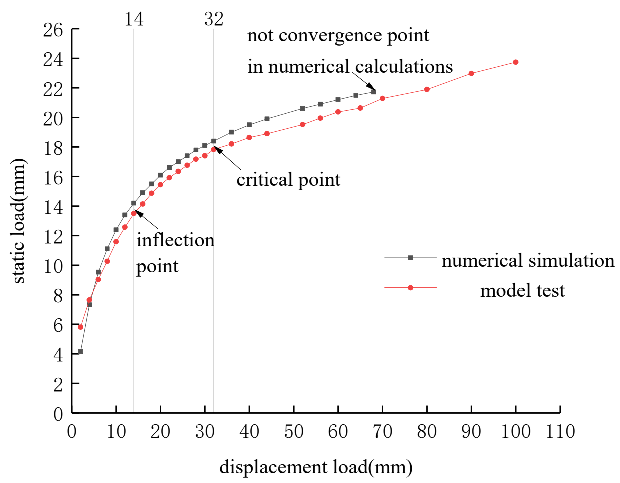



Figure 3. load - displacement curve comparison of pile top

As shown in Figure 3, inflection point and critical points appear in the same position, the errors of the bearing capacity are 5.2%, 3.2% respectively. It can be considered that the numerical model can be used to inversion the indoor model test.

## 4. Analysis of results

The horizontal displacement of pile and the bending moment of pile under the action of displacement load at all levels of pile top are shown in Figure 4 and Figure 5.

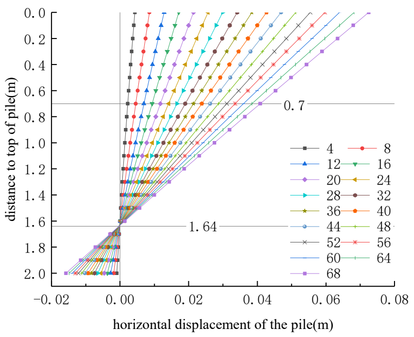



Figure 4. horizontal displacement of pile under different loads

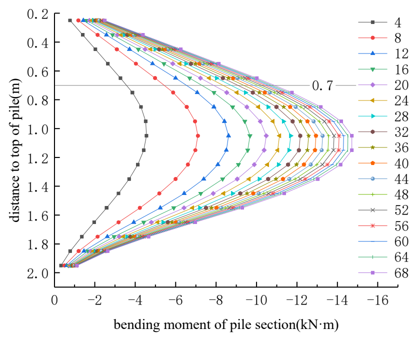



Figure 5. Pile bending moment diagram under different loads

As can be seen from Figure 4 and Figure 5, the pile is rotated at a certain point, in accordance with the rigid pile motion model proposed by Viggiani[12]. The distance between the center of rotation and the top of the pile is 1.64m and the distance to the ground surface is 0.94m. The bending moment of the pile has a linear growth in the cantilever segment, when the distance from the top of the pile is greater than 0.7m, the increasing trend of the pile's bending moment gradually slows down, the bending moment of the pile becomes the maximum when the distance from the top of the pile is 1.1m, and the bending moment tending to 0 near the bottom of pile.

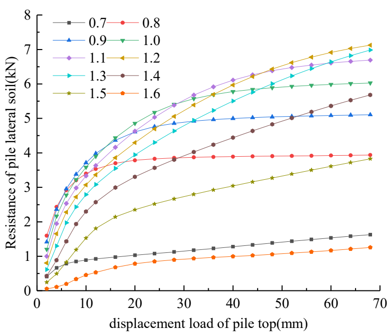



Figure 6. Soil resistance diagram under different loads

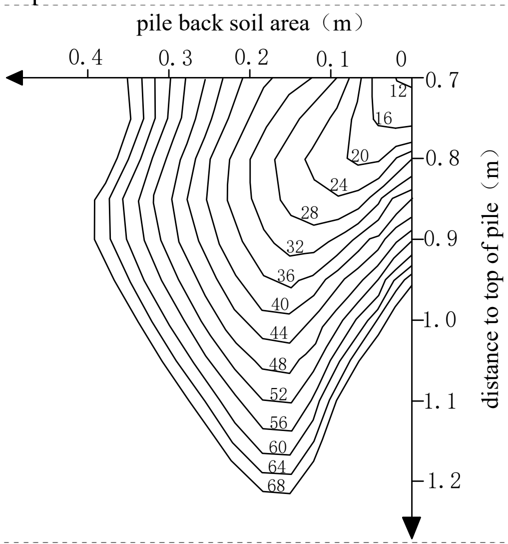



Figure 7. Contour line of the plastic strain zone under the displacement load

As shown in Figure 6, with the increase of the load, the lateral soil resistance of each section reaches the limit successively, and as the depth of the soil increases, the load required to reach the limit is greater. It is indicated that under the action of large displacement load, the pile side soil reaches the strength limit by layer, when entering the yield state, the soil resistance no longer increases with the displacement.

Figure 7 is the Contour line of the plastic strain zone under the displacement load of pile-top at all levels. It is shown from the graph that the plastic region of soils located on the back side of the pile has a certain directivity in the process of applying the load. The maximum range value of the plastic zone does not appear at the top of the pile, but a certain depth under the ground (which is different from the failure surface of the circular table based on the upper limit method theory in the literature [9], which assumes that the pile is smooth and specifies the geometric boundaries of the damaged area, the condition is too ideal to limit its applicability.), At this time, the upper soil has not been able to withstand more load increment, the load increment begins to be obviously assumed by the lower soil layer, which is consistent with figure 9, when the pile-top load exceeds 32mm, the soil resistance of the piles at 1.1m and above of the pile is basically no longer increasing.

**5. Conclusions and recommendations**

Based on the results of the model test, the lateral characteristics of rigid piles under large displacement are studied by numerical simulation method, the main conclusions are as follows:

（1） Under the action of lateral load, the variation of bending moment is closely related to the length of cantilever section and the position of turning point about rigid pile.

（2） As the load increases, the failure of the rigid pile shows that the soil is yielding by layer. The maximum soil Resistance cross section of the pile is gradually shifted down, and the plastic zone begins to expand obviously to the deep part after the ultimate load is reached.

（3） The research in this paper is based on model test and numerical simulation, which needs to be verified by field test.

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