Computer simulation and model test study on influence of water immersion degree on wind power generation pile stress

Weibo Yan¹, ², *, Xulong Gao¹, ², Hongwei Huang¹, ², Dongfa Liu¹, ², Jinlong Ma¹, ², Xinqin Hui³
¹College of civil engineering and mechanics, Lanzhou University, Lanzhou, China
²Key Laboratory of Mechanics on Disaster and Environment in Western China, Lanzhou University, Lanzhou, China
³DaTang Dingbian Wind Power Generation Co., Ltd., Dingbian, China

*Corresponding author: yanwb19@lzu.edu.cn

Abstract. The force of foundation piles in collapsible soil is a complex and important issue. Different degrees of collapsibility will have different effects on the force of foundation piles. In order to analyze and discuss the distribution and change law of the axial force and negative friction resistance of the foundation pile in moe detail, this paper summarized the existing research results on the influence of immersion collapsibility on the development of the axial force and negative friction of the foundation pile, and through model test research, the strain of the loaded foundation pile and the unloaded foundation pile under the same site conditions were measured as the site was wet. The test shows that the degree of collapsibility is positively correlated with the force of foundation piles in collapsible loess site. The presence or absence of a load on the top of the pile has a greater impact on the development process of the pile's force during the immersion of the site; but it has little effect on the distribution of the pile side friction when the site is fully immersed and saturated.

Keywords: Flooding, Collapsible site, Pile, The model test.

1. Introduction

Engineering construction in the western region of China has entered a period of rapid development. With the transformation of Chinese economic structure and the pursuit of more balanced and adequate high-quality development, the development of the northwestern region will receive further attention. Loess is widely distributed in many provinces including Shaanxi, Shanxi, Gansu, Inner Mongolia, Qinghai, etc., where the most typical large-scale loess landform in the world has developed, covering an area of 620,000 square kilometers. Unsaturated loess has the characteristics of high strength and low compression under natural humidity, but due to its special structure, it is prone to collapsing under conditions such as water immersion and compression, causing negative friction in the pile foundation, which will lead to the pile foundation. The base bearing capacity cannot be fully utilized, sometimes even causing damage to it. Therefore, it is very important to study the influence of site collapse on the force of foundation piles.
At present, there are many research results on the problem of negative friction of foundation piles at home and abroad. The effective stress method is recommended for the calculation of negative friction of pile foundation in the current "Technical Specification for Building Pile Foundations", and suggestions are given for determining the position of the neutral point and calculation formula [1]. Regarding the determination of the negative friction and the position of the neutral point, relevant scholars at home and abroad have also conducted a lot of and rich research [2-5]. Although the effective stress method is simple to calculate and convenient for engineering applications, there are also large deviations between the lower part of the pile and the actual situation, the calculated negative friction is conservative, and it is only suitable for situations where the relative displacement of the pile-soil is relatively large. The determination of neutral point is based on experience. In addition, many scholars have conducted a large number of experiments on load transfer functions and obtained some typical load transfer functions. For example, Zhao Minghua, Hu Qian, etc. used the hyperbolic stress-strain model to derive the calculation formula for the settlement of the pile side soil, and establish a load transfer function reflecting the relationship between the pile-soil interface shear stiffness coefficient and the depth [6]. Based on the load transfer method, Yu Guangming, Gong Weiming and others proposed a theoretical calculation method for the pull-down load of a single pile when considering non-Darcy flow consolidation and rheological coupling effects under large-area pile loading. The top deformation is solved iteratively, and the distribution of the down-load load of the pile body and the long-term change rule of the neutral point are obtained [7]. The load transfer method takes into account the nonlinear characteristics of the pile side soil, and the method is simple and clear. However, the selection of the load transfer curve has a great influence on the accuracy of the final calculation results, and it cannot consider the influence of the weak underlying layer, and it cannot reflect the strengthening and resistance of the pile side. Degenerate. In addition to the effective stress method and load transfer method, there are also elastic theory methods, shear displacement methods, etc., all of which propose solutions for the study of the force characteristics of pile foundations [8, 9]. These methods have their advantages, but they also have certain limitations.

Engineering test research can best directly reflect the characteristics of the pile foundation, so as to grasp the law of changes in the pile foundation force. Field tests are often carried out based on specific projects, which can systematically and accurately study the side friction of the pile foundation, the position of the neutral point of the pile, and the resistance of the pile end. For example, Xu Yuanlei used a pile foundation project in a tidal flat backfill site as an example, focusing on the analysis of the reasons for the excessive settlement of the pile foundation from the perspective of negative friction [10]. Such an example is of great reference for similar projects. However, the model test fully considers the size effect, boundary conditions and environmental factors, and due to its advantages of good economy, strong pertinence, strong simulation, etc. It is used in the study of the negative friction resistance, end resistance, and neutral point position of the pile foundation. Wide range of applications. For example, Tang Liyun and others carried out indoor model tests based on the predicted temperature field in combination with actual engineering cases, and studied the influence of the increase in atmospheric temperature on the negative friction resistance of the pile side in the frozen soil area through the change law of the pile side friction resistance of the frozen soil piles with different ages [11]. In order to study the change and distribution of negative friction of pile foundation in collapsible loess area, Zhuangfu Zhao et al. designed and completed the negative friction model test of pile foundation considering the collapsibility of loess [12]. Feng Zhongju and others through large-scale shear tests of the model, studied the influence of different moisture content and different coatings on the side of the pile foundation on the negative friction resistance of the pile foundation, and explored the weakening effect of various pile foundation surface coatings on the negative friction resistance of the pile foundation [13]. Therefore, based on the consideration of the size effect of the single pile in the model box and the boundary conditions, this paper simulates the collapsible loess site through model tests, and measures the stress and strain of the loaded and unloaded foundation piles under the same site conditions as the site is flooded. The development of changes in the degree of collapsibility, the influence of site collapsibility
on the force of foundation piles and the law of stress distribution changes are analyzed, bring reference significance to actual projects.

2. Model test

2.1. Site model

The test was completed in a model box with a length of 1.2m, a width of 0.6m and a height of 1.0m. A number of holes are punched at the bottom of the model box for the flow of seepage water, and the depth scale is marked on the inner wall of the box to provide a reference for the filling and tamping of the soil in the box. This model test uses homogeneous remolded loess as the soil around the pile to simulate the collapsible loess site and simulate collapsible loess with different collapsibility coefficients by controlling the degree of compaction. The test soil was taken from the excavated loess from the construction land of the Qingbaishi, Lanzhou City.

Fill the selected experimental soil into the model box, tamping evenly in layers, each layer is 50mm high, and the layers are shaved. Tamping the soil to the specified density by controlling the volume and quality of the soil under the condition of the natural moisture content determined by multiple samples, then let it stand for 30 days and its basic physical indexes are shown in Table 1.

Table 1. Basic physical indexes of the soil in the test.

| Physical index | Gs (g/cm³) | ρ (g/cm³) | ρd (g/cm³) | e₀ | n | Sr (%) | W_L (%) | W_P (%) | I_L (%) | w (%) |
|----------------|-----------|----------|-----------|----|---|--------|---------|---------|--------|-------|
| -              | 2.71      | 1.50     | 1.42      | 0.91| 0.476 | 15.87  | 27      | 13.5   | 13.5  | 7.01  |

2.2. Pile model

In the test, precast concrete piles were used for the pile body, with a length of 900mm and a diameter of 75mm. The pile body is made of PVC pipe as the outer mold, and concrete is poured inside. After molding, the entire outer mold is wrapped with epoxy resin on the outer mold. The distance between the pile and the boundary of the model box is 264mm, which is enough to eliminate the influence of the boundary effect and control the lateral deformation [14], [15].

2.3. Measuring system

Figure 1. Static strain collector.

In this test, the strain of the pile and the soil pressure at the bottom of the pile are measured to understand the changes in the axial force of the pile. The strain gauges are selected from BX120-3AA strain gauges, with a resistance value of 120±0.1Ω and a sensitivity coefficient of 2.08. When the pile is made, it is pasted on the outer mold, protected with waterproof glue and epoxy resin, and connected
to the uT7116 static strain with a wire. On the strain box of the analysis system, as shown in Figure 1, the connection method adopts a 1/4 bridge connection. An earth pressure box is pre-buried at the bottom of the pile, which is led out by a wire, and the earth pressure at the bottom of the pile is measured by a measuring device. The entire measurement system is shown in Figure 2.

3. Test method

3.1. Test overview
This test mainly studies the influence of the degree of collapsibility on the force of foundation piles in the collapsible site. A model pile under a loading condition and a pile model under a no-load condition are produced respectively. In addition to the top load, the other the relevant conditions are the same. The pile length is 900mm, the ratio of length to diameter is 12, and the depth of entry is 750mm.

The loading plan of the load pile uses the gravity loading method, and the loading is completed before the water is immersed. Standard weights are used when loading, and the load is divided into ten levels, each level is 100N, a total of 1000N. The total amount of water in the immersion scheme shall be subject to the complete saturation of all soil bodies in the model box under consideration of evaporation. The total water volume is divided into eighteen injections and sprayed evenly every eight hours to complete the immersion of the site model within six days. During the process, the pile body strain and the soil pressure at the bottom of the pile are continuously monitored.

3.2. Test data processing method
Before the measurement starts, the earth pressure cell and the strain monitoring system are calibrated, balanced and reset to zero. Measure the strain value $\varepsilon$ of the pile body and the reading $f$ of the soil pressure box at the bottom of the pile, then:

The axial force of the pile section is:

$$N_i = \pi r^2 E \varepsilon_i$$  \hspace{1cm} (1)

The average value of the negative friction resistance of the pile side at the i-th section of the pile body is:

$$f = \frac{N_i - N_{i+1}}{2\pi r l_i}$$  \hspace{1cm} (2)

In the formula: $E$ represents the elastic modulus of the pile; $N_i$ and $N_{i+1}$ represent the axial force of the i-th section and the i + 1-th section respectively; $l_i$ represents the length of the i-th section of the pile.

4. Analysis of experimental results

4.1. Grading loading of load piles before flooding
Before the site is immersed in water, the load piles are loaded in stages, and the measurement results are processed to obtain the corresponding pile shaft force development distribution map, as shown in Figure 3.
It can be seen from Figure 3 that the 1-2 level of load loading has basically no effect on the pile depth below 25cm; the loading of the first 5 levels has very limited impact on the pile depth below 30cm; After the sixth-level load is loaded, the axial force changes of piles with a buried depth of 35 cm and above are obviously affected. As the load increases step by step, the axial force growth at each monitoring point basically shows a linear change. Load in stages until all loads are added. During the whole process, the force of piles below the depth of 55cm is not affected by changes in the upper load. It is a typical friction pile.

4.2 Analysis of the axial force of the pile in the flooding stage
After the graded load is loaded and the pile body is stable, the site is immersed in water. During the immersion process, the force of the loaded pile and the unloaded pile body changes significantly, as shown in Figure 4 and Figure 5.
It can be seen from Figure 4 that after the first water supply, the axial force of the loaded pile with a buried depth of 55cm or more increased significantly, but at this time the axial force of the pile body was not transmitted to the bottom of the pile; as the amount of flooding continued to increase, the pile body The axial force at each measuring point shows an increasing trend as a whole.

Within eight hours after the eighth water addition (time of 64-72h), the axial force of the pile body increased greatly, and the axial force at the buried depth of 45cm increased the most, the maximum value was 375N; the ninth time of water addition (time was After 72h), the total flooding volume has reached half of the water volume required for full saturation of the site. At this time, the axial force transmission of the pile shaft reaches the bottom of the pile, and the pile end reaction force begins to appear at the bottom of the pile. As the water supply increases, the position of the maximum axial force of the pile body continues to move downward. After adding water for the last time (time is 144h), the maximum position of the pile shaft force reaches the buried depth of 65cm.

Although at 144h, the total flooding volume has reached the required water volume to fully saturate the site, the development of the pile shaft axial force has not stopped due to the suspension of water supply. After 16h of water stoppage (160h), the pile body force reached the maximum value of the entire test process, and the maximum position of the pile body axial force was moved down to the bottom of the pile. The maximum value of the entire pile body axial force reached 3188N, which exceeded the load on the top of the pile 3 times. Afterwards, the axial force at each point of the pile body began to slowly decrease, and the maximum position of the pile body axial force continued to move up, and finally stabilized at a buried depth of 45cm when the time reached 184h. In the whole process of the development of the axial force of the pile, the maximum value of the axial force of the load pile first moves down to the bottom of the pile, and then rises to the buried depth of about 45cm.

![Figure 5. Axial force diagram of unloaded pile.](image)

The axial force change of the unloaded pile as the control group during the flooding process is shown in Figure 5. It can be seen from Figure 5 that after flooding, the axial force of the pile starts to develop downward from the upper part of the pile and gradually increases. At the same time, the position of the maximum axial force of the pile continues to move downward. After the ninth water addition (time 72h), the axial force of the pile is about to develop to the bottom of the pile. At this time, the distribution of the axial force of the pile is basically symmetrical up and down, and the measured maximum axial force...
of the pile is 341.1N. After adding water for the twelfth time (96h), the pile end reaction force appeared at the bottom of the pile, and then as the water supply increased, the pile end reaction force continued to increase.

After the water supply was stopped, the development of the axial force of the unloaded pile did not stop, and the entire axial force of the pile continued to increase. After 40 hours of water shutdown (for time), the maximum position of the axial force of the pile was moved down to the depth of 65cm. The maximum value is 1948.8N. This maximum axial force is also the maximum value during the development of the pile shaft axial force during the entire flooding process; at this time, the pile tip reaction force reaches 1902.5N. Since then, the axial force of the pile at the depth of 55cm and below began to decrease, and the position of the maximum axial force of the pile began to move up, but the axial force of the pile at the depth of 45cm and above was still slowly increasing. As can be seen from the figure, during the process, the axial force of the pile with a buried depth of 57.5 cm does not change much. Similar to the performance of the loaded pile, in the whole process of the axial force development of the pile body, the position of the maximum axial force at first moves down and then have a rise, but the difference is that the maximum position of the axial force of the unloaded pile is always higher than the buried depth 65cm.

Comparing Figure 4 and Figure 5, it can be seen that the axial force at the bottom of the unloaded pile appears later than that of the loaded pile. After the water supply is stopped, the axial force of the loaded pile and the unloaded pile continues to increase for a period of time, but the maximum value of the axial force development process of the unloaded pile appears later. After the maximum axial force development of the pile body, the axial force fall of the loaded pile and the unloaded pile below the buried depth of 55cm has decreased, but the axial force of the pile body of the loaded pile is more than 45cm buried. The part of the unloaded pile whose buried depth is more than 45cm is always growing slowly. Whether it is a loaded pile or an unloaded pile, the maximum axial force of the pile body when it is finally stabilized appears at the buried depth of 45cm.

4.3. Analysis of pile side friction resistance during flooding

![Side friction resistance of load pile during flooding stage.](image)

*Figure 6. Side friction resistance of load pile during flooding stage.*
Through the distribution of the axial force of the two piles, the development process of the pile side friction resistance can be further analyzed and calculated. The specific conditions are shown in Figure 6 and Figure 7.

It can be seen from Figure 6 that before the load pile is immersed in water, 2/3 of the pile body is distributed with positive side friction, and the maximum positive friction resistance can reach 17.48kPa. As the amount of water increases, the positive frictional resistance of the upper part of the pile continues to decrease, and the positive frictional resistance of the lower part of the pile increases. After adding water for the ninth time (72h), the amount of water added reaches 1/2 of the amount of water required to fully saturate the site. The positive frictional resistance is mainly concentrated below the depth of 40cm of the pile body, and the pile end reaction force also appears at the bottom of the pile. In the next 24 hours (72h-96h), the negative friction resistance of the pile with a buried depth of 45cm or more appears and increases rapidly. After that, the negative friction resistance of the upper part of the pile continued to increase and developed downward, while the positive friction resistance of the lower part continued to decrease and eventually disappeared. At 184h, the position where the pile body has the greatest negative friction resistance drops from a buried depth of 30 cm to a depth of 40 cm, and the positive friction resistance again appears from the bottom of the pile and increases upward. By 334h, the development of pile side friction resistance is basically stable. At this time, the maximum positive friction resistance of the pile body appears at the bottom of the pile, with a size of 15.4kPa; at the same time, the negative friction during the entire pile side friction development process appears at the depth of 40cm. The maximum resistance is -34kPa.

![Figure 7](image_url)

**Figure 7.** Side friction resistance of unloaded pile.

The development of side friction of unloaded piles is different from that of loaded piles. As shown in Figure 7, due to no load, there is no side friction resistance of the pile body before flooding. After
immersion, the friction resistance starts to develop downward from the position where the pile body enters the soil. After the third time of adding water (24h), the positive and negative friction resistance of the pile body with a depth of more than 50cm are more obvious. At 48h, the curve of the distribution of the positive and negative friction resistance of the pile body is roughly symmetrical about the position of the buried depth of 30cm. With the increase of water immersion, the maximum value of the positive and negative side friction resistance of the pile body is increasing continuously. When the water was stopped at 144h, the position where the maximum positive friction resistance of the pile body appeared moved down to the bottom of the pile, and the position where the negative friction resistance of the pile body appeared continued to develop downward. By 184h, the negative friction of the entire pile body at the buried depth of 60cm or more appeared. This is also the time when the negative friction resistance of the pile body without load during the entire flooding period is the most widely distributed. After that, the positive friction resistance of the pile body began to rise from the bottom of the pile. By 238h, the development of the side friction resistance of the pile body is basically stable, the maximum positive and negative friction resistance of the pile body reaches the maximum value in the whole test process, and the maximum negative friction resistance reaches -32.94kPa, appearing at the buried depth of 40cm; The maximum positive friction resistance of the pile body appears at the bottom of the pile, reaching 15.12kPa.

4.4. Analysis of Neutral Point Location

The boundary point of the positive and negative friction resistance of the pile body is the position of the neutral point of the pile body. It can be seen from Figure 7 that the neutral point of the load pile body only appeared after 72h and moved down quickly to a position with a buried depth of less than 40cm. As the amount of water increased, the neutral point position continued to move downwards. At 160h, the positive friction resistance of the loaded pile body completely disappeared; in the following 24 hours, the neutral point position reappeared from the bottom of the pile and began to move upward. At 334h, the neutral point is basically stable near the lower 1/3 of the pile. It can be seen from Fig. 8 that the negative friction resistance of the pile body of the unloaded pile appears earlier, so the neutral point of the pile body has appeared within the first 24 hours and moved down quickly; by 48h, the neutral point position has reached the pile body 1/2 of the length of the soil. Afterwards, the neutral point position keeps moving down as the amount of water added increases. After the completion of water addition (at 144h), the neutral point position continues to move downwards, reaching the deepest position of the neutral point of the unloaded pile during the entire test at 184h. At this time, the neutral point is located at the depth of 60cm of the pile. After that, the neutral point moved up slowly with time, and stabilized near the lower 1/3 of the pile at 334h.

5. Conclusion

(1) The degree of collapsibility has obvious influence on the pile foundation stress of collapsible site. Regardless of whether there is a load on the top of the pile, the axial force of the pile and the side friction of the pile will increase significantly due to the increase in the degree of site collapse. The maximum axial force of the pile during the flooding process can reach as much as 3 times the load applied on the upper part. Which shows that the degree of collapsibility of the collapsible site has a great influence on the force of foundation piles.

(2) Foundation piles with different initial stress states are affected differently in the process of site immersion and collapse. When the initial positive friction resistance of the load pile gradually disappears with the site collapse, the axial force of the pile body is transmitted to the bottom of the pile faster than the unloaded pile due to the existence of the top load. And due to the existence of the top load, the load pile may temporarily appear as an end-bearing pile when the forward friction resistance of the pile body of the load pile disappears completely.

(3) After the neutral point of the loaded pile and the unloaded pile appears, it will move down as the degree of collapsibility increases. The neutral point will move to the lowest end when the negative
friction resistance is the most distributed, and then it will move up as time goes by. Move to 2/3 of the depth of the pile body into the soil.

(4) Regardless of whether a load is applied to the top of the pile, the distribution of positive and negative friction resistance of the pile body is basically the same when the foundation pile is stable after flooding. The maximum negative friction resistance is about 33kPa, and the position is 0.53 times the pile. At the depth of the body into the soil, the position of the neutral point is stable at 0.67 times the depth of the pile body into the soil. This shows that when the site conditions and the pile conditions are the same, the final result of the pile side friction development after the site is saturated with water has little relationship with the pile top load.

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