

Article

Model Test Study on the Bearing Mechanism of Inclined Variable Cross-Section Piles Using Transparent Soil

Qiang Ma ^{1,2} , Jianyu Li ², Lin Liu ² and Xuesong Lu ^{1,3,*}¹ School of Architectural Engineering, Huanggang Normal University, Huanggang 438000, China; maqiang927@163.com² Hubei Provincial Ecological Road Engineering Technology Research Center, Hubei University of Technology, Wuhan 430068, China; ljianyu1998@163.com (J.L.); 17786526184@163.com (L.L.)³ Huanggang Ecological Architecture and Renewable Resources Research Center, Huanggang 438000, China

* Correspondence: hglxs@126.com

Abstract: In view of the influence of the inclination and variable section on the pile stability and bearing capacity, this paper introduces particle image velocimetry (PIV) technology, and designs a transparent soil visualization model test. The experimental results show that, when the pile has a variable cross-section and inclination angle, the friction resistance on both sides of the pile increases. The vertical-load-carrying capacity of the 2% and 4% inclined piles with a variable cross-section is greater than that of the piles with inclinations greater than 8%. For model piles with the degrees of inclination of 2% and 4%, the variable-section inclined piles with diameters of 17 mm and 15 mm show significantly less settlement than the equal-section inclined piles. For the model pile with an inclination of 8%, the settlement of the inclined piles with a variable cross-section diameter of 17 mm is slightly smaller than that of the equal cross-section inclined piles. The change in variable cross-section and inclination angle has a large effect on the soil displacement around the pile, and the conclusions of this paper can provide guidance for the engineering application of variable cross-section piles.

Keywords: transparent soil; PIV technology; visualization; pile; variable; inclination



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1. Introduction

Pile foundations are commonly used for large bridges, buildings, and harbors due to their reliability. Variable-section piles offer advantages such as a high bearing capacity, minimal settlement and deformation, rapid construction, and strong horizontal resistance, making them widely adopted [1]. In engineering, vertical piles can also become inclined due to lateral loads, leading to different mechanical behavior compared to strictly vertical piles. The factors influencing inclined piles are complex. However, due to the intricate nature of variable-section piles, traditional pile foundation analysis methods are inadequate for understanding their mechanical behavior.

In their study on variable-section piles under horizontal loading, Ismael et al. (2010) [2] discovered that increasing the size of the pile body's variable section significantly enhances the pile's lateral bearing capacity and reduces displacement at the pile top. They attributed this improvement to the increased bending strength resulting from the larger cross-sectional area of the pile. Field tests on the horizontal bearing characteristics of variable-section piles reinforced the need for a comprehensive analysis of the pile foundation mechanisms, emphasizing the interplay between the pile bearing capacity and co-ordinated pile–soil deformation [3,4]. The horizontal loading and vertical loading performance of inclined piles in sandy soil were investigated by a model test, which is of great significance for recognizing the bearing and deformation characteristics of inclined piles in sandy soil [5]. Some scholars have combined variable-section piles with engineering to replace steel pipe pile foundations with variable-section piles to provide the required bearing capacity for offshore oil platforms [6]. Seo et al. (2016) [7] carried out a model test of a retaining

wall combined with an inclined pile support pit in marine clay, and the results showed that the inclined pile reduced the lateral displacement of the support structure by about 40%. Rajashree et al. (2001) [8] gave a numerical analytical solution for displacement by theoretical calculations for the force characteristics of inclined piles, developed a finite element model for a static and cyclic load analysis using an incremental iteration method, and gave a numerical solution for single-pile load displacement. Cao et al. (2016) [9] studied the properties of horizontally loaded inclined piles, pull-out inclined piles, and vertically loaded inclined piles in sandy soils through model tests, which is of great significance in recognizing the bearing and deformation characteristics of inclined piles in sandy soils. The current studies have ignored the soil crowding effect of the immersed piles, and are unable to accurately analyze how the disturbance of the surrounding soil during pile filling affects the bearing capacity of the foundation piles.

The real deformation of the soil body cannot be observed using conventional model tests and field tests. By laying earth pressure transducers inside the soil body, not only is it easy to be damaged, but it also has a large error, which makes it impossible to obtain accurate test results, and the number of data points that can be observed is also limited [10]. Transparent materials mimicking natural soil were chosen to simulate its properties. Various experiments were conducted to determine the physical and mechanical characteristics of these materials and apply them in model experiments studying soil deformation and displacement [11–15].

In the fields of agriculture and ecological engineering, the motion of granular media can be better understood by measuring the displacement field of the granular media and trends associated with the displacement can be better determined [16–18]. The PIV and image testing technique can be used to study the penetration characteristics of piles in sandy soils [19,20]. With the application of PIV technology, some scholars have carried out visualization tests of the pile loading settlement process [21–23]. Lehan et al. (2004) [24] utilized transparent soil visualization by embedding small black beads into it for immersion pile penetration testing. They tracked the movement of these beads using cameras to capture the entire displacement field of the soil, rather than focusing on displacement at specific points.

The current research primarily focuses on pile bearing capacity tests, with less emphasis on inclined pile bearing mechanisms. A comprehensive analysis of the pile behavior should consider both the pile's load-bearing capacity and co-ordinated deformation with the soil. Experimental studies often struggle to accurately and comprehensively measure soil displacement inside the pile body, limiting the understanding of pile–soil deformation. This paper utilizes transparent soil, PIV, and image testing techniques to continuously photograph the pile movement using a CCD camera. PIV technology is employed to design a transparent soil system for testing inclined pile bearing capacities without inserting measurements into the pile. The resulting images are processed using PIV to analyze the soil displacement around the pile, offering insights for engineering applications of variable-section inclined piles.

2. Model Test and Materials

2.1. Preparation of Transparent Soil

Transparent soil is synthesized from transparent materials and pore fluids with corresponding refractive indices [11]. Fused silica sand particles are hard and inert with good transparency, and mixing with pore fluids achieves good transparency [25]. Fused silica sand was selected from Xuzhou Xinyi Wanhe Mining (Jiangsu Test Electronic Equipment Manufacturing) in China, and the microstructures of the samples and 80× magnification are shown in Figure 1.

According to the experimental specification (GB 50139-2014) [26], geotechnical experiments, and particle grading curve shown in Figure 1, the basic physico-mechanical parameters of fused silica sand are shown in Table 1. The pore liquid is a mixture of n-dodecane and No. 15 white oil prepared at a mass ratio of 1:4, which is physically stable

and non-corrosive relative to calcium bromide solution. In nature, at 24 °C, the refractive index of the transparent mixed solution measured using an Abel refractometer was 1.4586. The refractive index of the colorless transparent plexiglass in the model box is 1.49, which is the same as that of the transparent soil, and it does not deflect the light, so it can completely achieve the effect of transparency, and the effect on the test results can be ignored, as shown in Figure 1c.

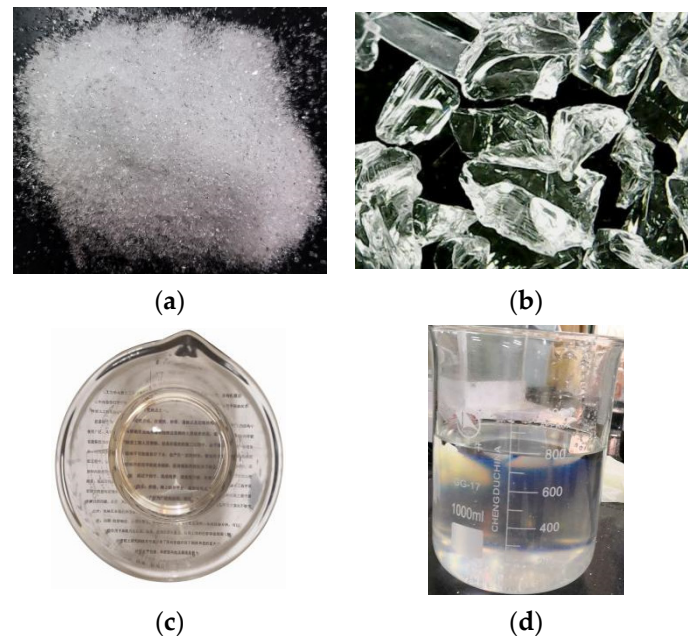


Figure 1. Test materials: (a) fused silica sand sample, (b) enlarged microscopic structure, (c) top view of transparent soil sample, and (d) main view of transparent soil sample.

Table 1. The main parameters of the test preparation of fused silica sand.

Properties	Value
Grain size	0.5~1 mm
Specific gravity (Gs)	2.186
Coefficient of uniformity (Cu)	1.83
Coefficient of curvature (Cc)	1.00
$\rho_{\min}/\text{g}\cdot\text{cm}^{-3}$	0.970
$\rho_{\max}/\text{g}\cdot\text{cm}^{-3}$	1.274
ψ	39.4
Refractive	1.4585
C (Mpa)	0.23
φ (°)	31.46

2.2. Variable-Section Piles

A single pile model is produced, which contains 1 equal-section pile and 12 variable-section piles. As shown in Figure 2, the diameter of the pile with uniform cross-section is defined as the same, and the diameter of the pile with variable cross-section is different, and the variable diameter ratio is the ratio of the upper and lower diameters of the pile. In this paper, the length of the model pile is 200 mm, and the pile body is polished before the test to ensure the roughness of the pile body. The inclination angle of the pile is the ratio of the overall length of the pile projected on the horizontal plane to the actual length of the pile (%) according to China's "Technical Code for Building Foundation Pile Test" (JGJ106, 2014) [27]. The model pile used in the model test is made of colorless transparent plexiglass with a diameter of 20 mm, and the degree of inclination of the pile body is set to 0%, 2%, 4% and 8%. Chari et al. (1983) [28] carried out model tests in uniform sandy soil to investigate

the ultimate bearing capacity of piles under loads of different inclination angles, and found that the inclination of inclined piles with an inclination angle of less than 10° hardly affects the ultimate bearing capacity of the piles. The variable-section diameter is set to 17 mm, 15 mm, and 13 mm.

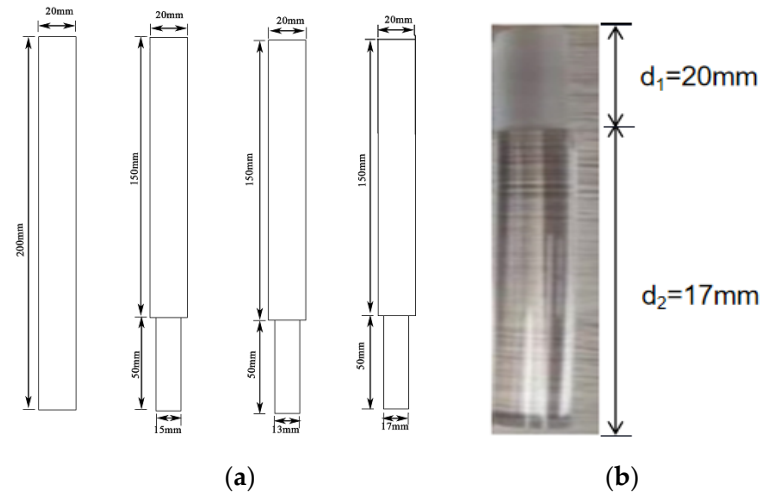


Figure 2. Model pile: (a) variable-section model pile, and (b) $d_1/d_2 = 20/17$ model pile.

2.3. Model Test Box

The model test is scaled down to 1:20. The model test box used is made of colorless transparent plexiglass, and the model test box is a cube with an opening at the top. Due to the use of loading program, loading boundary effect will affect the accuracy of the test results. In order to attenuate the impact of the boundary effect, the model test box size is greater than 5 times the diameter of the pile. This paper produces the length, width, and height of $400\text{ mm} \times 200\text{ mm} \times 200\text{ mm}$, respectively, with a wall thickness of 8 mm, as shown in Figure 3.

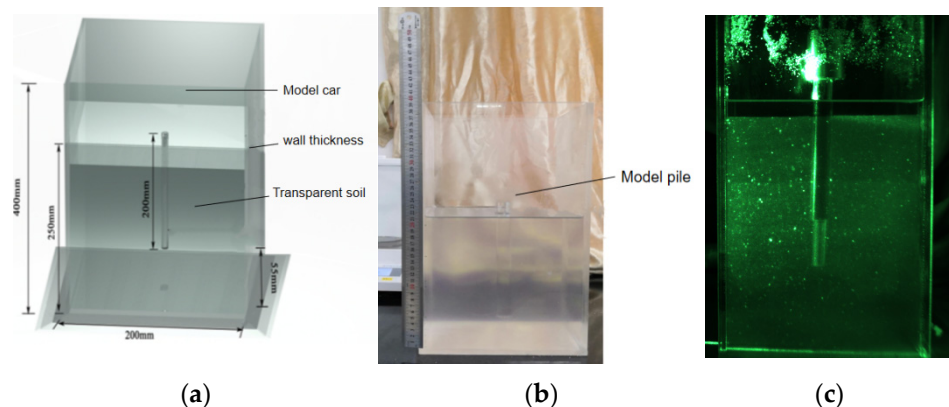


Figure 3. Model test box: (a) model rendering, (b) picture of real products, and (c) scattering field.

2.4. Visual Model Test System

The pile sinking visual model system is shown in Figure 4, which mainly includes high-speed CCD camera, the source light of laser, fully automatic loading system, computer image processing system, etc. The loading device of model test system is shown in Figure 4a,b. The fully-automatic loading system used in the model test adopts the automatic static pressure mode. The displacement sensor of the sinking pile visualization system can be adjusted to 0–400 mm and the loading range of the load is 0–30 kN.

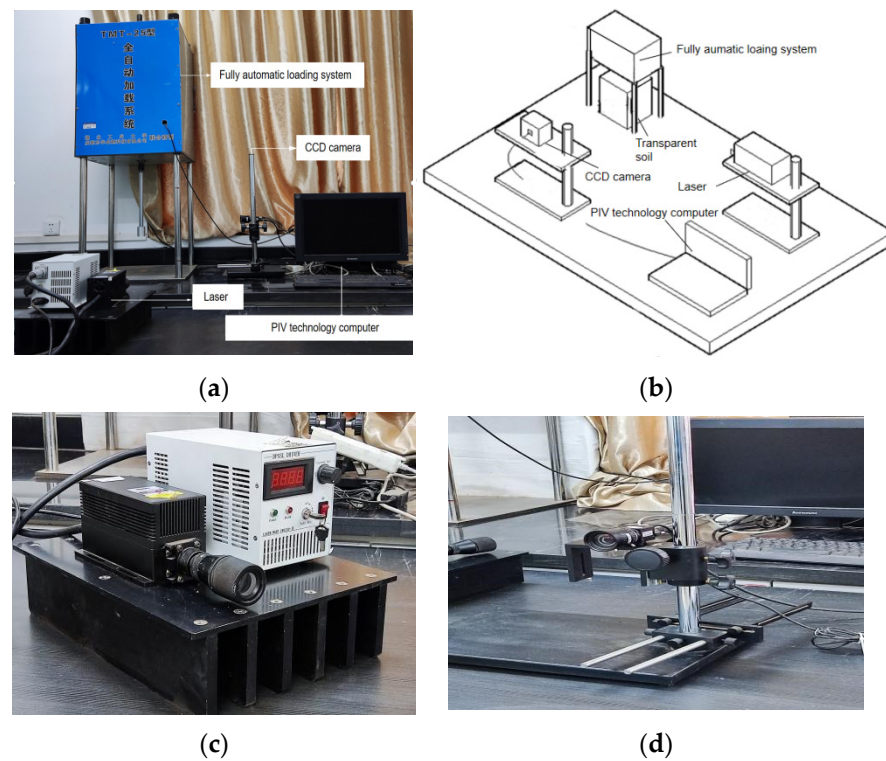


Figure 4. Visualization model test system of pile driving: (a) model test device, (b) model test system diagram, (c) laser, and (d) CCD camera.

The laser light source used in the immersed pile visualization system is the EP532-2W semiconductor laser produced by Lai Chuang Laser Technology (see Figure 4c). The laser is a HeNe laser, and a linear converter is used in the experiment to convert the point light source into a scattered field.

The CCD camera used in the visualization system is the MV-VD120SM CCD high-speed industrial digital camera produced by Xi'an Visions Digital Image Technology (see Figure 4d), with a resolution of 1280×960 , frame exposure mode, frame number of 15, and exposure time of $100 \mu\text{s}$ –30 s. The CCD high-speed camera captures and photographs images of the sunken piles over a short period of time using its own software.

2.5. Measurement System

PIV is a technology based on image processing; the actual process needs to transform image co-ordinates and physical co-ordinates to each other, in PIV analysis. Through image matching technology, the image is matched by standard function relationship. as shown in Equation (1) [29]:

$$C(\Delta x, \Delta y) = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m, n) g(m + \Delta x, n + \Delta y) \quad (1)$$

where M and N represent the length and width of the form, respectively; f is the distribution function of the scattered points at the center point co-ordinates (m, n) of an image block in the image at time t_1 ; similarly, g denotes the distribution function at time t_2 ; and Δx and Δy represent the displacement increments in the x and y directions, respectively.

Through the displacement of the correlation function at t_1 to t_2 , the displacement field of the soil around the pile is calculated.

2.6. Test Flowcharts and Programs

The test flowchart was shown in Figure 5.

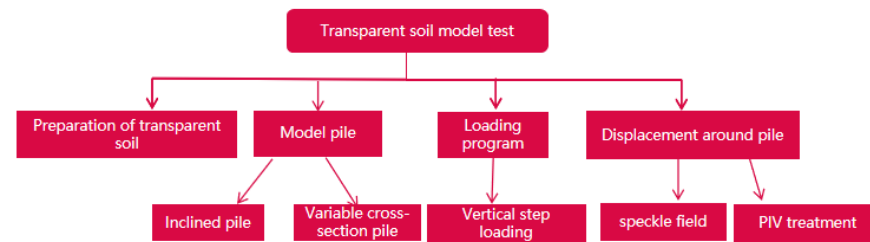


Figure 5. The test flowchart.

As shown in Table 2, we have the model of a pile with a section ratio of 20/17, and the upper Figure 2b shows the model of a pile with 20/17 variation ratio. For descriptive purposes, the cross-section at locations where the pile diameters are different is defined as a variable cross-section, and the large diameter section on the top accounts for 1/4 of the total length. The 16 groups of experiments were carried out by varying the variation ratio and inclination angle of the variable-section piles.

Table 2. Test scheme of the visualization model test.

Case Number	Degree of Inclination/%	Upper Section Diameter d_1 /mm	Pile Length L /mm	Lower Section Diameter d_2 /mm	Apply Vertical Load Q /N
C_1	0	20	200	20	50/75/100/125/150/175/200
C_2	2			15	
C_3	4			17	
C_4	8			13	

During the experimental process, the pore liquid was diverted with a glass rod and mixed with fused silica sand, the vacuum was pumped through a vacuum pump, and the pile was taken to be pre-positioned [30,31], and the total thickness of the transparent soil laying was about 250 mm. In order to obtain clear graphics, the testing process in this study was carried out in a dark room with a constant ambient temperature controlled by air conditioning to 20 °C up and down (20 °C transparent soil ensures better clarity).

Through the pre-test, the estimated vertical pile bearing capacity is about 200 N; according to the Chinese technical code for test of building foundation pile (JGJ106, 2014), the following loading plan and abortive loading conditions are formulated: Loading is graded according to 1/10 of the estimated ultimate bearing capacity of the test pile. When the pile top settlement is less than 0.01 mm in 10 min and the load maintaining time is not less than 30 min, the next level of load can be added, and the pile top settlement under a certain level of load is more than two times of the previous one and has not been stabilized in 30 min, or a clear inflection point occurs at the tail end of the pile top settlement–force relationship curve (Q – S curve) under a certain level of load; then, the loading is terminated. The pictures before and after loading are processed by PIV and other software, and the two-dimensional displacement field of the soil around the whole pile is obtained by analyzing each section of the laser.

3. Test Results and Discussion

The displacement relationship of the soil around the piles under vertical loading was investigated by using an indoor modeling test [21]. This study refers to the method. Figure 6 shows the load–settlement curves of pile tops under vertical loads for model piles with different reduction ratios and inclinations in the indoor model tests (the curve results presented in the figure are the average of the results of the two sets of replicate tests, and the results of the parallel tests are slightly different but with the same pattern). Based on the load–displacement curves, the effects of the variation ratio and inclination angle on the bearing capacity of variable-section inclined piles were analyzed separately.

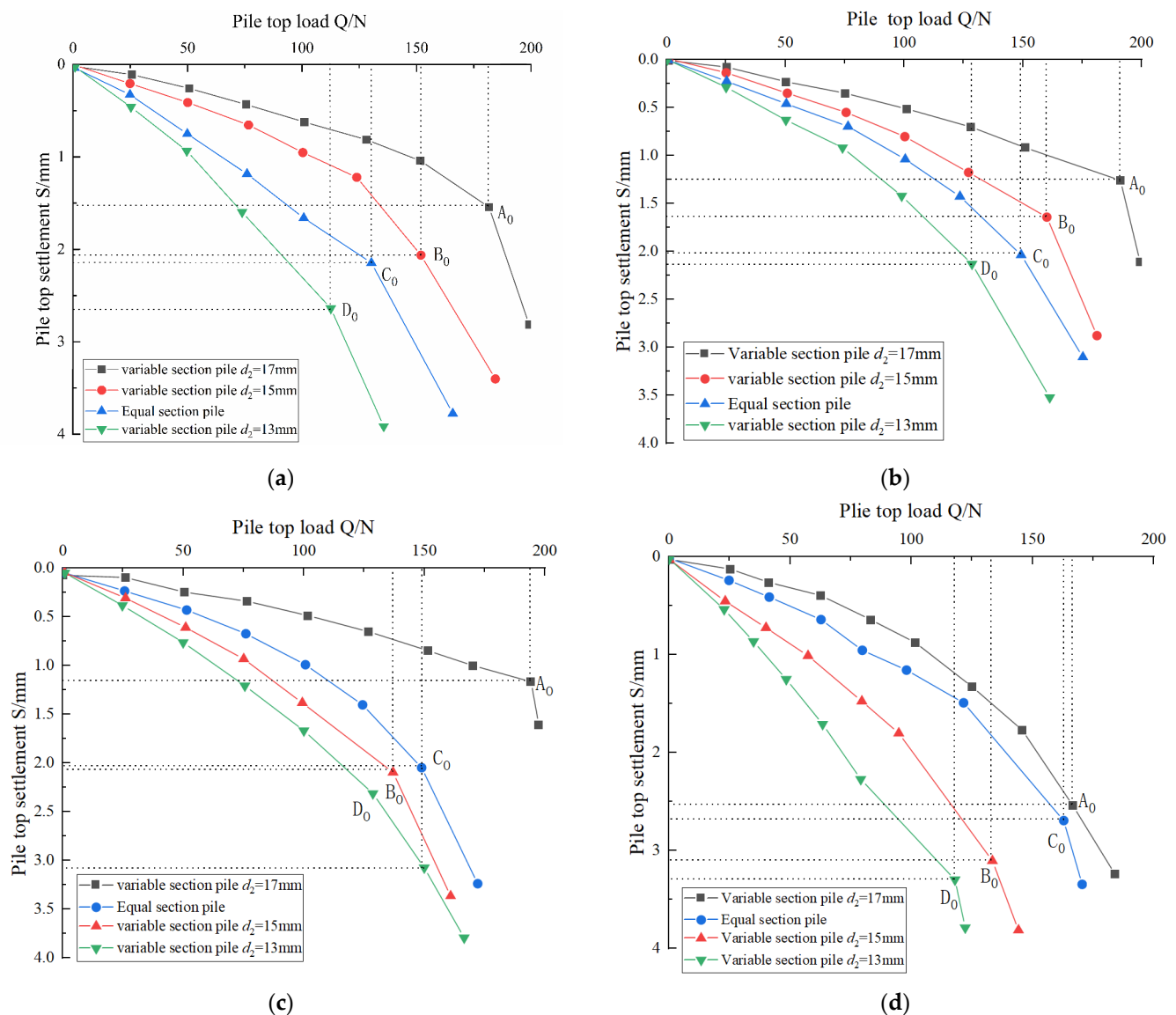


Figure 6. Load–displacement of pile with different inclinations: (a) 0%, (b) 2%, (c) 4%, and (d) 8%.

3.1. Effect of Variable Diameter Ratio on Vertical Bearing Characteristics of Piles

In Figure 6a, the top load–settlement curves of the three variable-section piles in the figure also belong to the steep-drop type, and it can be seen from the figure that the vertical ultimate bearing capacity of the single pile for equal-section piles is 130 N, and the vertical ultimate bearing capacity of the single pile for variable-section piles with pile variable cross-section diameters of 17 mm, 15 mm, and 13 mm are 180 N, 150 N, and 110 N, respectively. When the length of the variable section is certain, and the ratio of the variable-section pile is 20/17, the pile's bearing capacity can be increased by up to 14%.

In addition, observing the settlement at the top of the pile, the slope of the load–settlement curve becomes larger when the radial dimension of the variable section becomes smaller for a certain length of the variable section. However, the slopes of the load–settlement curves for variable-section diameters of 17 mm and 15 mm are smaller than those for equal-section piles; i.e., their corresponding settlements are smaller than those for variable-section straight piles. This indicates that, when the pile body has a variable cross-section, the soil body under the variable cross-section of the pile body is compacted to a certain extent during the load bearing process, and the lateral friction resistance of the pile body is improved.

Analyzing the phenomenon, the soil at the lower part of the variable section of the pile body shares part of the pressure transferred from the top of the pile, thus reducing the pressure of the soil at the end of the pile, thus reducing the settlement of the end of the pile. The slope of the curve of the 15 mm variable-section pile is smaller than that of the equal-section pile in the figure, mainly because the resistance produced by the pile body due to the variable section is, to a certain extent, slightly larger than the lateral frictional resistance lost, resulting in the ultimate bearing capacity of the curve remaining similar to that of the complete pile. When the ratio of the variable diameter is appropriate, the vertical bearing characteristics of the monopile are basically unaffected.

3.2. Effect of Inclination Angle on Pile Bearing Characteristics

In Figure 6b,c, for the model piles with a 2% and 4% inclination, the settlements of the pile tops were significantly smaller than those of the equal-section inclined piles when the variable-section diameters were 17 mm and 15 mm, respectively. For the model pile with an 8% inclination, the settlement of the pile top is smaller than that of the equal-section inclined pile only when the diameter of the variable section is 17 mm.

When the inclination of the variable-section inclined pile is 2%, the vertical ultimate bearing capacity of the single pile of the equal-section inclined pile is 150 N, and the vertical ultimate bearing capacity of the single pile of the variable-section inclined pile with variable-section diameters of 17 mm, 15 mm, and 13 mm are 190 N, 160 N, and 130 N, respectively. In terms of the vertical ultimate bearing capacity of the single pile, when the length of the variable section is certain, and the ratio of the variable-section piles with variable-section diameters is 20/17, the vertical ultimate bearing capacity of the pile is the highest. And, when the length of the variable section is 1/4 of the pile length and the radial dimension of the variable section is 75% of the complete pile diameter, the load carrying capacity of the pile can be increased by as much as 26%.

When the inclination of the variable cross-section inclined pile is 4%, the vertical ultimate bearing capacity of the single pile of the equal cross-section inclined pile is 160 N, and the vertical ultimate bearing capacity of the single pile of the variable cross-section inclined pile with diameters of 17 mm, 15 mm, and 13 mm are 200 N, 150 N, and 140 N, respectively. In terms of the vertical ultimate bearing capacity of the single pile, when the length of the variable cross-section is certain, and the ratio of the variable cross-section of the pile is 20/17, the vertical ultimate bearing capacity of the pile is the highest. When the variable-section length is 1/4 of the pile length and the radial dimension of the variable section is 75% of the complete pile diameter, the load carrying capacity of the pile can be increased by as much as 37%.

This indicates that, when the pile body has a variable cross-section and the inclination angle is suitable, the soil at the lower part of the pile body at the variable cross-section is compacted to a greater extent because of the existence of the variable cross-section and the inclination angle in the pile foundation during the bearing process. The lateral frictional resistance of the pile body is improved, and the soil at the lower part of the variable section of the pile body shares more pressure from the top of the pile, so the pressure of the soil at the pile end is reduced, thus reducing the settlement of the pile end. The slope of the curve for the 4% inclination 15 mm variable-section pile is smaller than that of the 2% inclination 15 mm variable-section inclined pile in the figure, mainly because of the different resistance produced by the inclination of the pile body.

In Figure 6d, when the inclination is 8%, the vertical ultimate load capacity of the single pile for equal-section inclined piles is 97 N. The ultimate load pattern of variable-section inclined piles with different vari-diameter ratios is slightly different from that of variable-section straight piles. The vertical ultimate load capacity of the variable-section inclined piles with diameters of 17 mm, 15 mm, and 13 mm are 100 N, 80 N, and 70 N, respectively. In terms of the vertical ultimate load capacity of the single pile, when the length of the variable section is certain, and the variable-section piles have a ratio of 20/17, the pile has the highest vertical ultimate load capacity, but the increase in the capacity of

the friction piles is not obvious. This is due to the fact that the pile body is inclined too much, which makes the contact instability between the pile body and the soil increase, and the existence of the variable section makes the soil attain a certain degree of compaction. The increased lateral frictional resistance and the soil pressure at the top of the pile shared by the lower soil at the variable section of the pile are less than the instability due to the excessive inclination of the pile.

3.3. Displacement of Soil around Pile under Working Load and Failure Load

The images taken during pile uplift were post-processed by PIV software V3.7.16, and the grayscale images taken before and after the deformation of the soil body were segmented into many grids, each of which was called an interrogation block. The interrogation block before deformation was matched with the grayscale image after deformation, and the position of the interrogation block before and after deformation was determined according to the peak correlation coefficient, from which the average displacement of the block was obtained. Similar operations are performed on all interrogation blocks before deformation to obtain the entire displacement field

Figures 7–12 show the soil displacement fields around the pile under working and failure loads. In the displacement vector diagrams, the arrow size and length indicate the magnitude of soil displacement, while the arrow direction shows the direction of the soil particle movement.

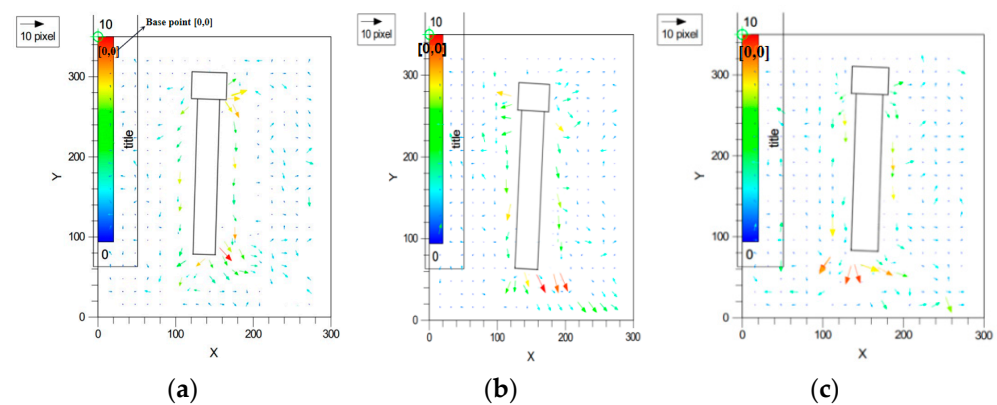


Figure 7. Contour cloud and displacement vector of soil under working load (degree of inclination is 2%): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

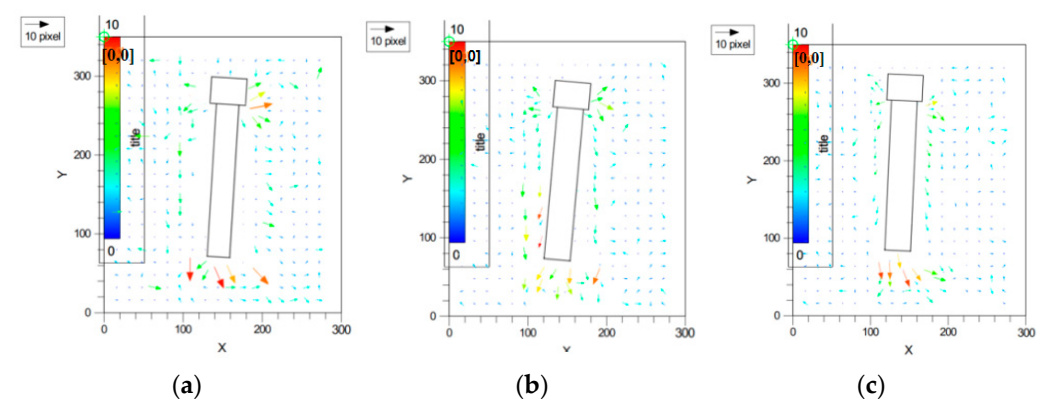


Figure 8. Contour cloud and displacement vector of soil under working load (degree of inclination is 4%): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

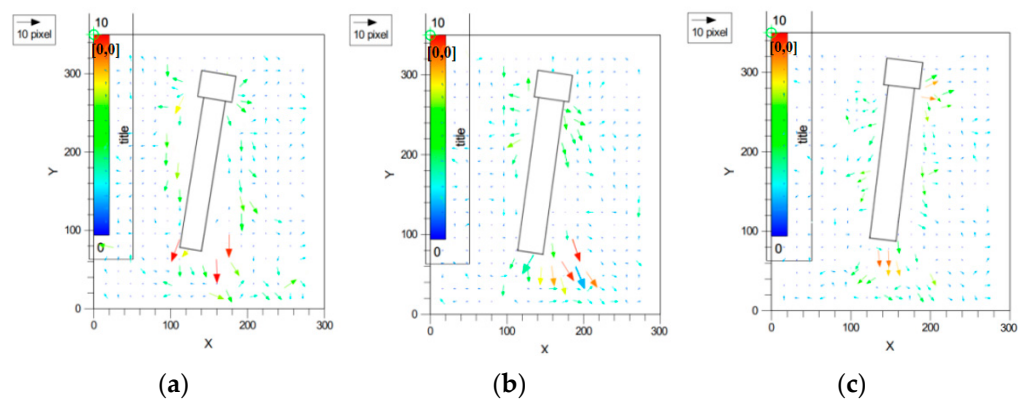


Figure 9. Contour cloud and displacement vector of soil under working load (degree of inclination is 8°): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

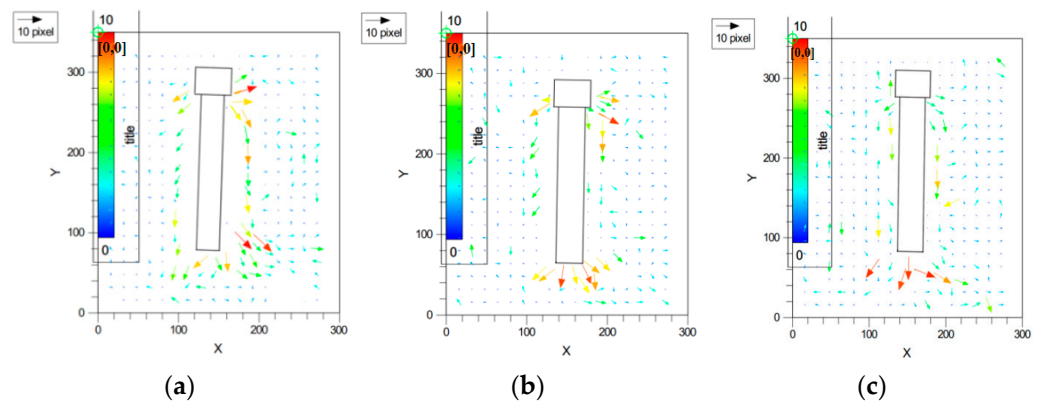


Figure 10. Contour cloud and displacement vector of soil under failure load (degree of inclination is 2°): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

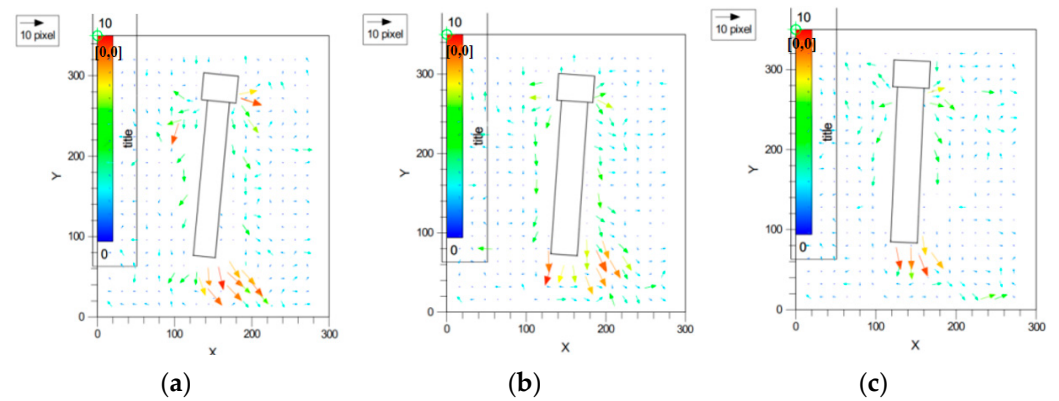


Figure 11. Contour cloud and displacement vector of soil under failure load (degree of inclination is 4°): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

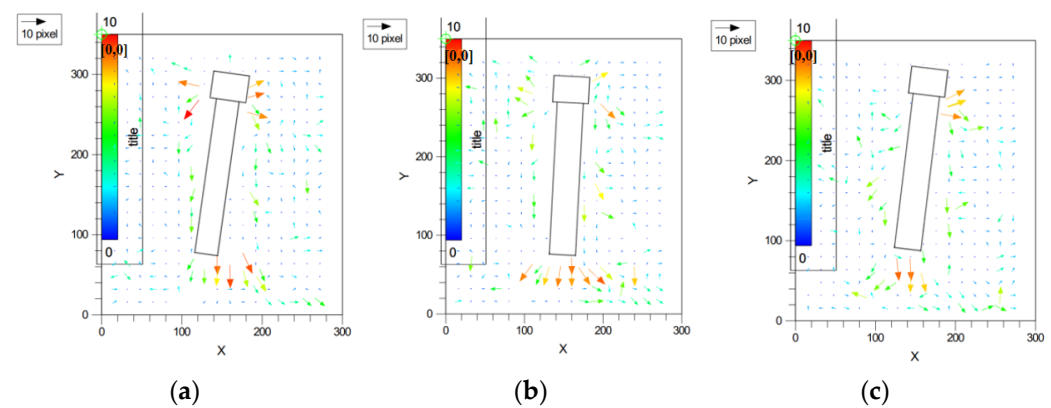


Figure 12. Contour cloud and displacement vector of soil under failure load (degree of inclination is 8%): (a) $d_2 = 13$ mm, (b) $d_2 = 15$ mm, and (c) $d_2 = 17$ mm.

3.4. Displacement of Soil around Pile under Working Load

In Figures 7 and 8, the two-dimensional soil deformation around variable cross-section inclined piles with 2% and 4% inclinations was analyzed under different section reduction ratios. The test results showed that, under the working load (when the load is below the ultimate vertical load capacity), slight changes in the section reduction ratio and inclination lead to relatively uniform soil deformation, especially at the vari-dimensional cross-section and the pile end. The deformation and its influence are also small at the pile sides and ends.

In Figure 9, when the pile is inclined 8%, displacement changes little with increasing inclination. The section reduction ratio affects pile displacement more than the inclination degree. As the variable cross-section diameter decreases, the contact area between the pile and surrounding soil increases. This contact area size directly impacts the soil displacement range around the pile, making the variable section's influence on the soil greater than that of the inclination.

3.5. Displacement of Soil around Pile under Failure Load

In Figures 10 and 11, under the failure load (when the load reaches the vertical limit capacity), the displacement field of the soil around the pile expands compared to the working load (when the load is below the vertical limit capacity), and the direction of some soil particle displacements changes. The influence of the variable section and inclination on the soil remains consistent with that under the working load. When the pile loses its bearing capacity and the surrounding soil undergoes general shear failure, soil deformation extends from local to global. Yuan found that, under load, the vertical displacement of the soil around the pile compacts, forming a wedge-shaped region [32].

In Figure 12, the variable section does not enhance the bearing capacity of inclined piles. When the inclination is fixed, decreasing the variable cross-section diameter significantly reduces the influence range on the surrounding soil at the cross-section and pile end. As the diameter decreases, the soil deformation around the pile accelerates from local to global, and the pile's bearing capacity gradually decreases.

During failure loading, the displacement direction of the soil around the pile changes. The soil at the pile end and variable cross-section shows similar behavior, with the deformation expanding from local to global. This indicates general shear failure, and the pile loses its load-bearing capacity.

4. Conclusions

In response to the problem where the existence of variable-section pile inclination affects the bearing capacity of foundation piles, PIV technology was introduced to design transparent soil visualization model tests to carry out research on the bearing mechanism of variable-section inclined piles. For the test results that cannot be obtained in previous conventional studies, the following conclusions can be drawn:

1. When the pile body is slightly inclined, the soil on both sides of the pile body increases the friction force on it; the vertical bearing capacity of inclined piles with a 2% and 4% inclination is greater than that of vertical piles with a higher-than-8% inclination.
2. For variable-section piles, the slope of the load–settlement curve becomes larger when the radial size of the variable section is too small (the ratio of the variable section to the diameter is 20/13), and, under the same load level, the corresponding settlement of variable-section monopiles with a small radial size of the variable section is larger, and, for the diameter of the variable section of 17 mm and 15 mm, its corresponding settlement is smaller than that of the variable-section straight piles.
3. The change in the variation of the variation ratio at the variable section has a greater effect on the two-dimensional deformation of the soil around the pile than the inclination. The presence of a variable section does not improve the bearing capacity of variable-section inclined piles at inclination angles that are too large.

But there are many problems that need to be improved urgently: From the consideration of the test site conditions and materials, the nature of the soil of transparent soil is a single saturated sandy soil, while the geological conditions in the actual geotechnical engineering are more complicated. Compared with the objects measured in the traditional pile foundation test, no relevant measurements were made for the soil displacement at the pile end, bending moment of the pile body, and soil stress at each place of the pile perimeter and pile end, and the changes in the above parameters under different vertical loads could not be monitored and quantitatively analyzed. The follow-up study can improve the status quo of the test study, which can be improved from the nature of the soil layer, soil type, and other soil materials used in the test.

Author Contributions: This work is the result of collaboration among all authors. Q.M.: supervision, resources, funding acquisition, conceptualization, and writing—review and editing. J.L.: writing—review and editing, validation, software, methodology, investigation, and data curation. L.L.: writing—review and editing, supervision, and methodology. X.L.: conceptualization, supervision, validation, methodology, and formal analysis. All authors have read and agreed to the published version of the manuscript.

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