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Analysis of Group Pile Bearing Modes of Permeable Pile Dam with Different Incoming Flow Angles

Yingzhi Zhao [a], Xing Zhao [b,c*], Wenjiao Zhang [b,c] and Mingcong Lv [b,c]

[a] School of Civil and Transportation, North China University of Water Resources and Electric Power, Zhengzhou-450045, Henan, China.
[b] Yellow River Institute of Hydraulic Research, YRCC, Zhengzhou 450003, China.
[c] Key Laboratory of Lower Yellow River Channel and Estuary Regulation, MWR, Zhengzhou 450003, China.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Study Protocol

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ABSTRACT

Based on ABAQUS finite element analysis software, the group piles and single piles under different incoming flow angles are compared and calculated, the horizontal bearing characteristics of the group piles of permeable pile dam under different incoming flow angles are analyzed, the pile-soil force is solved, and the change rules of the load-displacement characteristics, the displacement distribution of the pile body, and the distribution of the pile body bending moment are analyzed in detail. The study shows that: for the group piles with flow angles of 0° and 45°, the stresses from the upstream piles to the downstream piles tend to increase along the flow direction, and a stress concentration occurs at the downstream pile; for the group piles with flow angles of 90°, the stresses gradually increase from the central pile to the piles on both sides, and the stress

**Corresponding author: Email: 948608992@qq.com;*

concentration area is distributed at the outermost pile. With the increase of the incoming flow angle, the horizontal bearing capacity of the whole group of piles shows an increasing trend, but due to the effect of the group piles, the bearing capacity of the unit piles is smaller than that of the single piles; The displacements of the group piles at different incoming flow angles were greater than those of the single piles, and the turning points were all at about 12 m below the mud surface; With the increase of incoming flow angle, the group pile starts to change from rigid deformation to flexible deformation, the maximum bending moment of the pile body decreases, and the maximum value of the bending moment of the pile body occurs at the burial depth of 5 m. The maximum value of the bending moment of the pile body decreases with the increase of incoming flow angle.

Keywords: Permeable pile dam; inite element simulation; horizontal bearing capacity; ABAQUS.

1. INTRODUCTION

Permeable pile dam [1] belongs to a new type of river improvement building, compared with the traditional groin engineering [2-4], the advantage of this type of building is that in addition to river control, it can also regulate the relationship between water and sand around the pile dam, after the dam to slow down the flow of silt to create a beach, and at the same time, because of its water permeability, it can minimize the downcutting of the riverbed due to the local energy conversion [5-6]. Since the 1970s, China began to use concrete permeable piles as river improvement projects, and has been applied to the Yellow River, Tarim River, Qiantang River and other places. Because of its foundation depth, strong not to seize, the material composition of the soil is more complex, after the dam can slow down the flow of silt, large floods can also be flooding the roof and other characteristics and by the yellow workers more and more attention [7-8]. At present, it has been applied in the project of Weitan project, Kuibaijiao project, Zhangwangzhuang project, Dong'an project and other projects in Henan Province [9].

The research on the bearing characteristics of pile dams mainly includes experimental research, theoretical analysis and numerical simulation, etc. The research results are of guiding significance for the design and construction of the group piles of permeable pile dams, but at present, there are fewer researches on the horizontal bearing capacity of the group piles of permeable pile dams, and most of the scholars focus on the research of the single piles and abutments. Most commonly, horizontal loading tests are performed on monopile foundations to investigate the relationship between displacement-load changes in pile foundations [10]. In addition, field tests can be combined with a variety of analytical methods [11-13] to investigate the horizontal bearing characteristics of more complex pile foundations or the vertical bearing capacity of pile foundations [14]. In terms of numerical calculations, the researchers established numerical models with the help of finite element software, finite difference software and pile foundation analysis software, and carried out parametric sensitivity analyses of pile foundation bearing capacity. Most of the scholars used ABAQUS finite element analysis software to simulate the pile foundation [15-16], and investigated the variation of its effect on the pile bearing capacity by changing various structural parameters (pile diameter, pile length, pile spacing, etc.) of the pile foundation [17-18]. In addition, scour will also have a certain impact on the horizontal bearing capacity, scour depth is larger, the horizontal bearing capacity discount is more obvious; scour will reduce the vertical bearing capacity of the pile foundation, and the overall scour is more obvious than the impact of local scour [19-20].

As can be seen from the current status and development of research at home and abroad, previous scholars have carried out many studies on bridge abutments and wind power monopile foundations, but the bearing capacity of the group piles of permeable pile dams has a certain degree of uncertainty, and the different headwater angles have a greater impact on the bearing capacity of the group piles. In view of this, this paper uses numerical simulation calculation and theoretical analysis methods to carry out the research on the horizontal bearing capacity of group piles of permeable pile dams under different flow angles, so as to provide scientific theoretical support for the construction and application of the permeable pile dams in the lower reaches of the Yellow River channel improvement project.

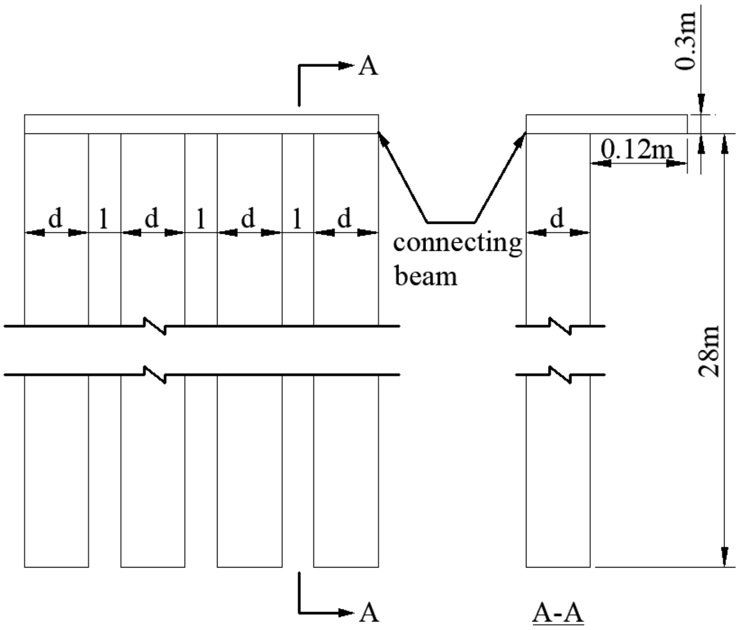


Fig. 1. Pile structure type

1.1 Project Overview

The Dong'an Project is located in Wuzhi County, Jiaozuo City, Henan Province, at the confluence of the Yellow River and the Qin River. The river section where the Dong'an Project is located has been systematically improved since the 1980s.The Dong'an project is a single-row reinforced concrete piles structure with a length of 28 m, a diameter of 0.8 m and a spacing of 1.2 m between the centers of adjacent piles. A working bridge is provided at the upper part of the pile dam, and a continuous girder is cast for two adjacent pile dams during construction to form a continuous pile row with a height of 0.12m and a beam width of 2m, as shown in Fig. 1. The project was constructed in 2000 and will be completed in 2020. After years of operation, the concrete structure of the pile dams of the Dong'an project has been severely worn out, and the siltation of sediment between adjacent piles has blocked the overflow channels between the piles and reduced the effectiveness of the pile dams in slowing down the flow and siltation. The center axis of the pile dam also shifted under the long-term action of the water flow.

2. FINITE ELEMENT MODELLING

2.1 Parameter Selection

Through the ABAQUS finite element analysis software precision modelling, the numerical model is selected from a section of ten-pile structure in the actual project to take 1:1 establishment. The model structure consists of three parts: connecting beams, group piles, and soil, with the group piles connected by connecting beams. In order to avoid the influence of soil boundary effect, then the theory needs the soil boundary is not affected by the loading of the pile dam, based on the research experience of previous scholars: the soil principal structure in the finite element model is selected Mohr-Coulomb model. The width of the soil body is taken as 25m, the length is taken as 50m, the height is taken as twice the pile burial depth of 52m, and the loading angle is set according to the incoming flow angle (That is, the angle between the loading direction and the pile axis). The table of parameters is shown in Table 1.

2.2 Division of the Grid

The mesh of connecting beams, group piles and soil body are all constructed using linear reduced-integral three-dimensional hexahedral solid cells (C3D8R), and structured mesh delineation with hierarchical encryption is adopted. Encrypted meshing in the pile body and pile-soil contact part, the mesh can be more rough in the non-focus area at the edge of the soil body, as shown in Fig. 2. In order to ensure the calculation accuracy and optimize the calculation time at the same time, the final model meshing is taken as 7W quantity through several simulations.

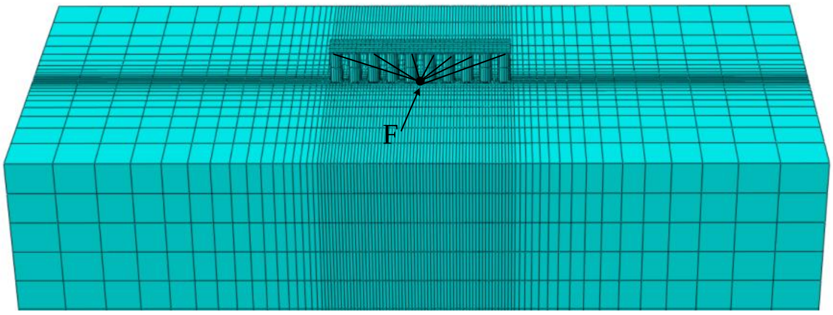


Fig. 2. Mesh diagram of finite element model

Table 1. Parameter selection for the model

Category	Density ρ/kg/m^3	modulus of elasticity E/pa	Poisson's ratio γ	internal friction angle ψ/（°）	Cohesive force c/pa
Pile	2500	2.55E+10	0.2	——	——
Soil	1000	2E+7	0.3	30	10000

2.3 Selection of Ultimate Bearing Capacity

In order to compare the horizontal bearing capacity of permeable pile dam group piles under different incoming flow angles, seven sets of control models were set up, with incoming flow angles of 0°(along the direction of pile axis), 15°, 30°, 45°, 60°, 75° and 90°. The calculated horizontal bearing capacity-displacement curves are shown in Fig. 3. According to "Technical Specification for Pile Foundation of Building", "The calculation of single pile and group pile foundation suggests to take the horizontal displacement of the pile top at the ground level as 10mm as the permissible deformation", so this paper takes 10mm as the limit displacement of group pile.

The horizontal bearing capacity of the group pile is gradually increased when the incoming flow angles changes from 0° to 90°, and the horizontal bearing capacity is increased by 0.1%, 0.96%, 3.46%, 6.63%, 8.89%, and 9.89% respectively compared with that at each angle of 0°. It can be seen that the horizontal bearing capacity is the largest when the incoming flow angles is 90°, as shown in Fig. 4.

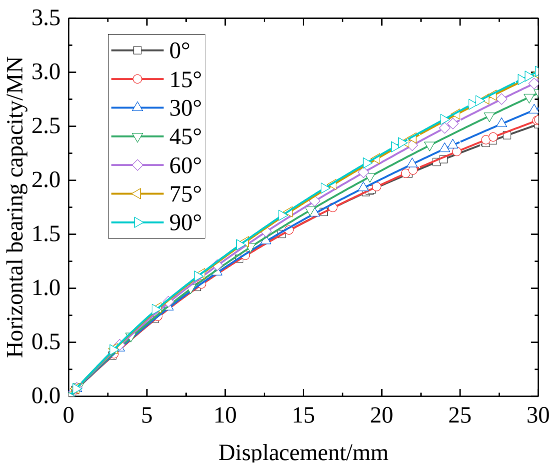


Fig. 3. Horizontal bearing capacity-displacement curves of group piles under different incoming flow angles

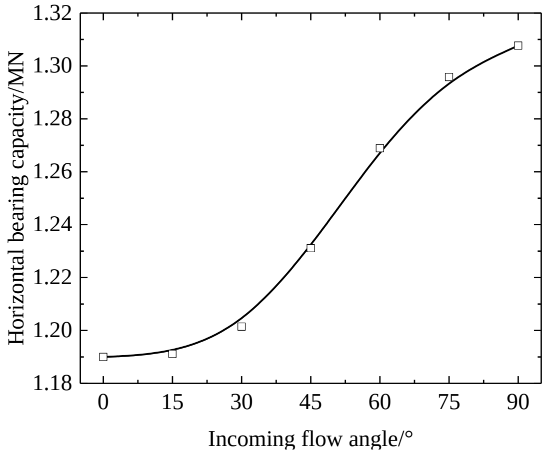
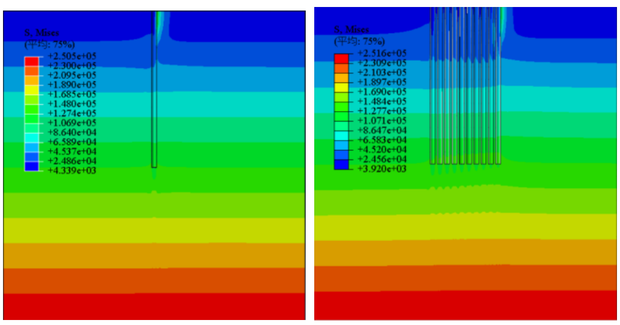


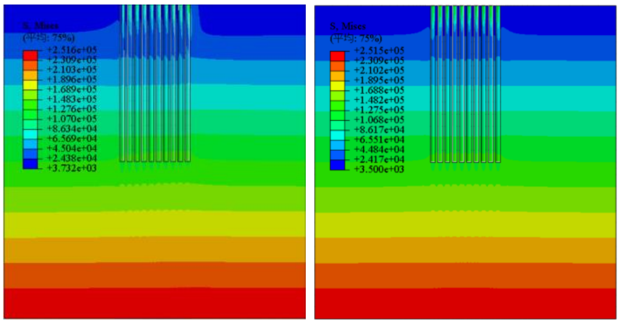
Fig. 4. Variation curve of horizontal bearing capacity of group piles with incoming flow angle

3. DAMAGE ANALYSIS OF SOIL MODELS

In order to compare the soil damage state of group piles and single piles under different incoming flow angles, three flow angles were selected: 0°, 45° and 90°.The principal stress distribution clouds and equivalent plastic strain clouds of the four sets of pile dams were obtained by ABAQUS software, as shown in Figs. 5-6. Shallow soil will first reach plastic state due to its low strength, leading to the bending of the pile body to the depth, and the bending process will exert horizontal compression on the deep soil, so that the horizontal resistance of the soil body along the direction of the pile body will gradually increase .Due to the application of horizontal loads, the stresses in front and behind the monopile show an increasing and decreasing trend, respectively, and a stress concentration is generated in front of the pile (Fig. 5a); The group piles with headwater angles of 0° and 45° showed an increasing trend of stress from upstream to downstream piles along the headwater direction, with a stress concentration at the downstream-most pile (Fig. 5b, c); For the group piles in 90°direction, the stress gradually increases from the central pile to the piles on both sides, and the stress concentration area is distributed at the outermost pile (Fig. 5d). With the increase of the flow angle, the plastic deformation region of the whole soil body gradually increases due to the increase of the contact area between the pile body and the soil body, but the damage degree of the soil body gradually decreases .As shown in Fig. 6, the plastic strain is highest at the downstream-most pile at 0° and 45° and direction along the loading direction, which will be the first to undergo damage, similar to the monopile deformation region ; For a group of piles in 90° direction, the stress concentration area is distributed in the outermost pile, resulting in the same and maximum plastic strain on both sides of the piles, and thus the piles on both sides will be damaged first and at the same time.

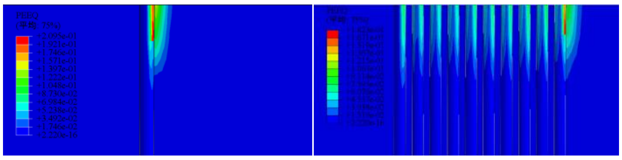


（a） single pile （b） group piles0°

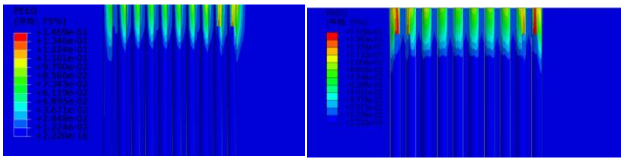


（c）group piles45° （d）group piles90°

Fig. 5. Cloud chart of principal stress distribution



（a）single pile （b）group piles0°



（c）group piles45° （d）group piles90°

Fig. .6 Equivalent plastic strain cloud

4. ANALYSIS OF THE EFFECT OF INCOMING FLOW ANGLE ON HORIZONTAL BEARING CAPACITY

4.1 Horizontal Load Bearing Capacity Analysis

Comparison of horizontal bearing capacity calculations for group piles and single piles at different incoming flow angles: 0°, 45°, 90°, as shown in FigS. 7-8. Calculation results show that: with the increase of the flow angle, the horizontal bearing capacity of the whole group of piles shows an increasing trend, respectively: 1.19MN, 1.23MN, 1.31MN, compared with the horizontal bearing capacity of the single pile of 0.19MN, the trend of increase is obvious, and the maximum reaches 6.9 times. However, due to the group pile effect, the bearing capacity is not a simple superposition of individual piles, resulting in the horizontal bearing capacity of the unit pile of the group piles being smaller than that of the single pile, and the horizontal bearing capacity of the unit piles at the three groups of headwater angles are 119kN, 123kN, and 131kN, which are reduced compared with the horizontal bearing capacity of the single pile.

4.2 Pile Displacement Analysis

A displacement load is applied to the pile at ground level to bring the displacement at ground level to the ultimate displacement. As shown in Fig. 9, the displacement and deformation of the group piles are larger than that of the single piles at the same position below the mud surface and at different incoming flow angles. Due to the increase in the number of piles, the stiffness of the overall group piles increases, in order to reach the limit of the final displacement, which results in the group piles' displacement being larger than that of the single piles at the same position below the mud surface. As the angle of incoming flow increases, the degree of deformation of the group piles shows a decreasing trend. The turning point of the piles remains basically the same, at about 12m below the mud surface.

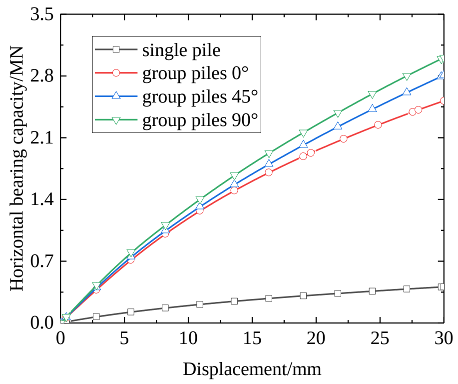


Fig. 7. Horizontal bearing capacity-displacement curves for monolithic piles

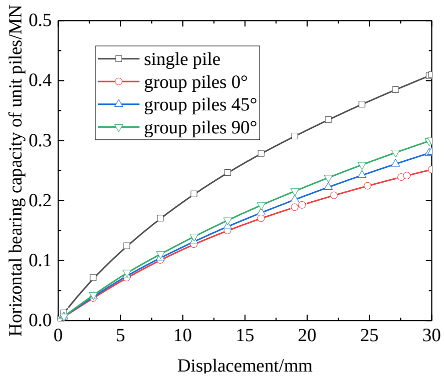


Fig. 8. Horizontal bearing capacity-displacement curves of unit piles

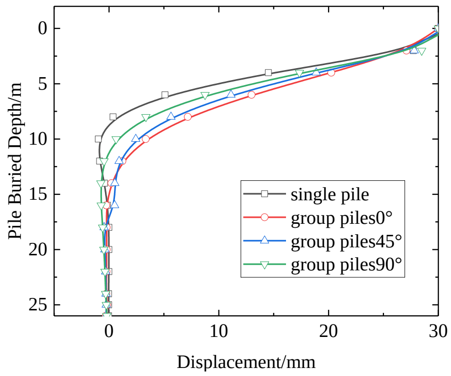


Fig. 9. Displacement curves of piles

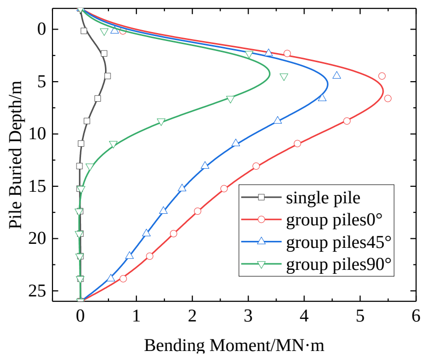


Fig. 10. Bending moment distribution curve of pile body

4.3 Distribution of Bending Moment of Pile Body

As shown in Fig. 10, with the increase of pile depth, the bending moment of the pile body shows the trend of increasing and then decreasing, and the maximum value of the bending moment occurs at the burial depth of about 5m, where the pile body is most prone to bending damage. The maximum bending moments of group piles under three sets of incoming flow angles were 5.49 MN·m, 4.58 MN·m, and 3.64 MN·m, which tended to increase significantly compared with the maximum bending moment of 0.49 MN·m for single piles. With the increase of incoming flow angle, the maximum bending moment of the pile body shows a decreasing trend, and the anti-bending point of the single pile and the group pile under 90° incoming flow angle occurs at 15m burial depth. This is due to the incoming flow angle is less than 90 °, in the direction of the soil along the pile row to produce resistance, as the incoming flow angle decreases, the soil resistance gradually increases, the pile row direction of the group pile stiffness increases, at this time the group pile began to change from flexible deformation to rigid deformation, the most downstream pile stress concentration is gradually obvious, the maximum bending moment of the pile body is then increased.

5. CONCLUSION

（1）For the group piles with incoming flow angles of 0° and 45°, along the incoming flow direction, the stresses from the upstream piles to the downstream piles tend to increase, and a stress concentration is generated at the downstream pile, which in turn is the first to be damaged; For a group of piles with an incoming flow angle of 90°, the stress gradually increases from the middle pile to the two side piles, and the stress concentration area is distributed at the outermost pile, and the outer piles will be damaged first and at the same time.Therefore, the effect of side piles should be considered first in a specific project.

（2）With the increase of the incoming flow angle, the horizontal bearing capacity of the whole group pile shows an increasing trend and reaches 6.9 times of the single pile bearing capacity at the maximum, but due to the influence of the group pile effect, the bearing capacity of the unit pile is smaller than that of the single pile bearing capacity; Since the overall stiffness of the group piles is larger than that of the single piles, the displacements of the group piles at different incoming flow angles are larger than that of the single piles at the same location, and the turning points are all at about 12m below the mud surface; The maximum value of the bending moment of the pile appears at the buried depth of 5 m. With the increase of the incoming flow angle, the group piles begin to change from rigid deformation to flexible deformation, and the maximum bending moment decreases accordingly.In practical engineering, the reduction of bearing capacity of group piles due to group pile effect and the change of group pile stiffness due to the magnitude of burial depth should be taken into account.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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