Opinion Article

The influence of the presence or absence of subdivision plate on the horizontal bearing characteristics of suction pile dam

Abstract: To explore the influence of subdivision plate on the horizontal bearing characteristics of suction pile dam, through the method of finite element analysis, under the condition of keeping the relevant parameters of suction pile dam consistent, the subdivision plate is added inside the bucket foundation to study the horizontal bearing capacity characteristics of four kinds of suction pile dam bucket foundation, such as single bucket, 4 bucket, 6 bucket and 8 bucket. The results show that the bearing mode of suction pile dam with bulkheads is basically similar to that of suction pile dam without bulkheads. With the increase of the number of bulkheads, the effect of bulkheads on the improvement of horizontal bearing capacity gradually appears. When the horizontal ultimate bearing capacity is reached, the bearing capacity can be increased by 60.8 % at most. With the increase of the number of buckets in the bucket foundation, the earth pressure on the outer side of the passive zone and the inner side of the active zone of the bucket foundation gradually decreases, indicating that the existence of the bulkhead plate effectively shares the load transferred from the upper part of the bucket foundation, improves the synergy degree of the bucket-soil inside the bucket foundation of the suction pile dam, and reduces the extrusion strength between the bucket-soil in the passive zone.

Keywords: suction pile dam ; sub-compartment plate ; load bearing characteristics ; soil pressure ; numerical simulation

1. Introduction

The Yellow River is a river with lots of silt and disasters, and the flood and sediment disasters are serious. The control of the Yellow River, especially the control of the Yellow River estuary, has always been a very difficult and important matter. The development of a new type of river channel control project applicable to the Yellow River can stabilize the estuary flow path and transport more sediment to the offshore area, which is an important way to solve the problems such as the difficulty of controlling the Yellow River regime and the high cost of emergency rescue [1]. On this basis, a new type of suction pile dam has been developed by referring to the permeable pile dam widely used in the middle and lower reaches of the Yellow River and the tubular foundation widely used in the field of deep-sea wind power. As shown in Figure 1 below, the suction pile dam is a new type of estuary regulation engineering structure developed on the basis of the permeable pile dam widely used in the middle and lower reaches of the Yellow River and the tubular foundation widely used in the field of deep-sea wind power. The structure is composed of suction cylindrical foundation at the lower part and pile group at the upper part. It has the advantages of mass prefabrication on land, rapid installation of multi-pile integration, zero residual recovery and transfer of water injection and low cost, and has a wide application prospect.

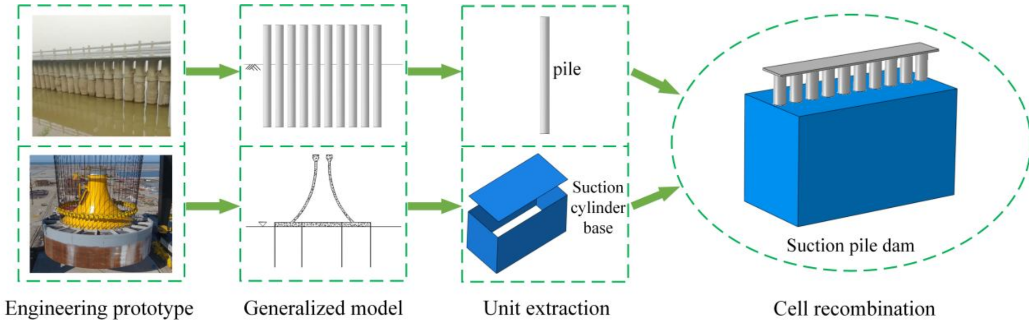


Fig.1 Structure diagram of suction pile dam

The influence of subdivision plates on the bearing capacity of foundation is usually not considered in the design of suction pile dam shell foundation, but the existence of subdivision plates has certain influence on the horizontal bearing capacity and bearing characteristics of suction pile dam. Barrel foundation has been widely used in the deep sea field, but it is still rare in the estuary management, so the offshore barrel foundation is taken as a reference. Many scholars have conducted researches on the bearing capacity of barrel foundation, and accumulated a lot of valuable experience in theoretical methods, numerical simulation and model tests[2-4]. However, there are few researches on the influence of subdivision plates on the bearing characteristics of barrel foundation. Le Conghuan et al[5] studied the mechanical and bearing characteristics of barrel foundation with subdivision plates by using numerical simulation. When the horizontal limit load is reached, the horizontal bearing capacity of barrel foundation with subdivision plates is increased by 18.3% compared with that of barrel foundation without subdivision plates. Based on the numerical simulation method, Xiao Zhong et al[6] studied the influence of cross-shaped subdivision boards on the one-way bearing capacity and failure modes of barrel foundation, and proposed a simplified calculation formula for the one-way bearing capacity of suction barrel foundation with cross-shaped inner partition. Based on silty clay foundation, CAI Zhengyin et al[7] studied the influence of honeycomb subdivision boards on the bearing characteristics of composite cylindrical foundation under different rotation states and different structural sizes, and evaluated the effect of the form, height and thickness of subdivision boards on the bearing capacity of foundation, and concluded that subdivision boards would not change the trend of Angle variation with load level, but could significantly improve the bearing capacity of foundation. Lian Jijian[8] studied through test and finite element analysis simulation that under the combined action of horizontal load and bending moment, the subdivision plate provides a large uplift bearing capacity for the barrel foundation, and the distribution law of earth pressure on the inside and outside side wall of the barrel and the earth pressure on the roof.

To solve the above problems, in order to quantify the influence of with or without subdivision plates on the horizontal bearing characteristics of suction pile dam, a numerical analysis model of suction pile dam is established by using ABAQUS software to explore the ultimate horizontal bearing capacity of suction pile dam with or without subdivision plates under horizontal load, the failure mode of barrel foundation and the distribution law of earth pressure inside and outside the barrel foundation. The bearing mode of the pile dam under the condition of different number of subdivision barrels is clarified, which provides support for foundation treatment, optimal design and bearing capacity calculation of suction pile dam.

2. Finite element calculation model

By using ABAQUS finite element software, the horizontal bearing characteristics of suction pile dam are analyzed. The research object of this paper is the suction pile dam. The relevant parameters of the pile group on the upper part of the suction pile dam are set by referring to an actual project of permeable pile dam in the lower Yellow River [10]. The total length is 2m, the outer diameter d=0.8m, the height above the mud surface of the cylinder foundation of the suction pile dam is h=2m, and the wall thickness is tp = 25mm. The foundation height of suction pile and dam barrel (H)=7m, barrel length A=12m and barrel width B=6m. Under the condition that the relevant parameters of suction pile and dam are consistent, subdivision plates are added inside the barrel foundation to study the horizontal bearing capacity characteristics of four kinds of suction pile and dam barrel foundation forms, including single barrel, 4 barrel, 6 barrel and 8 barrel. Fig. 2 (a) ~ (d) are finite element models for the arrangement of different number of subdivision barrels of cylinder base. The specific model parameters are shown in Table 1 and Fig. 3.

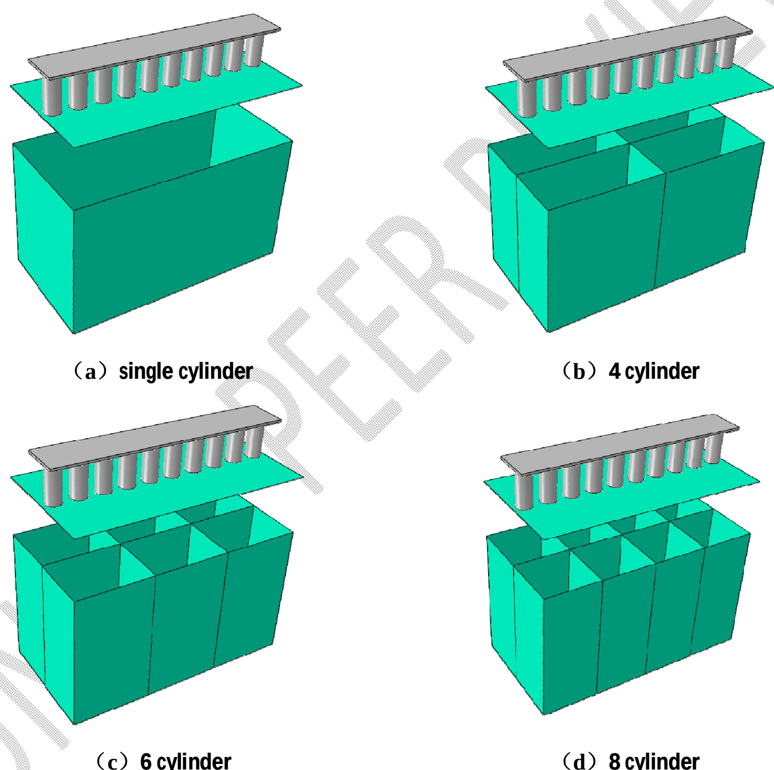


Fig.2 Finite element model of different cylinder foundation subdivision cylinder number arrangement

Table 1 Calculation conditions

Calculated working condition	Depth/height of cylinder in soil（m）	Cylinder length（m）	Cylinder width（m）	Thickness of cylinder wall（mm）	Pile spacing（m）	Subdivision arrangement	Bulk volumem^3
single cylinder	7	12	6	25	0.4	1x1	16.80
4 cylinder						2x2	19.95

6cylinder						2x3	21.00
8cylinder						2x4	22.05

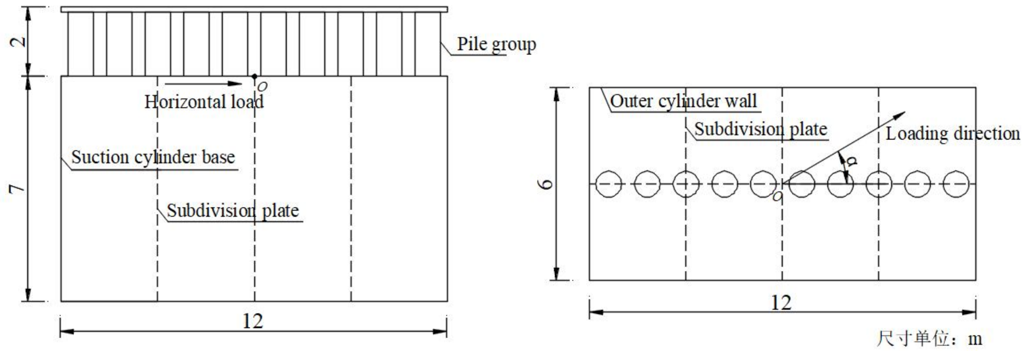


Fig. 3 Suction pile dam structure size and loading diagram

The friction between the foundation pile and the foundation cylinder in the suction type pile dam is increased by the relevant process treatment, and the friction coefficient is 0.3. Mohr-Coulomb elastoplastic constitutive model was adopted for soil foundation. Density ρ=1000kg/m^3, elastic modulus E=20MPa, Poisson ratio υ=0.3, and internal friction Angle was 30°. The elastic constitutive model is adopted for steel of suction pile dam foundation. The density ρ=7850kg/m3, elastic modulus E=210GPa, Poisson ratio υ=0.3; The concrete damage plastic constitutive model was adopted for the upper part of the suction pile dam and the permeable pile dam. The density ρ=2500kg/m3, elastic modulus E=25.5GPa, Poisson ratio υ=0.3.

In the calculation, the finite element model of soil mass and suction pile dam is established by three-dimensional solid element in hexahedral eight-node reduced integral format. In order to reduce the influence of the soil boundary effect calculation results, the soil length is 50m, the width is 25m, and the depth is 50m. The lateral boundary of the soil is constrained in radial direction, and the bottom boundary is completely constrained. The Coulomb contact model is adopted for the contact between soil and cylinder and the contact between pile and cylinder, and the friction coefficient is set tangentially, and the friction coefficient is 0.3. The normal direction is free contact, and the two sides can be relatively separated. Ground stress balance is carried out before loading to eliminate the additional effect of structural gravity.

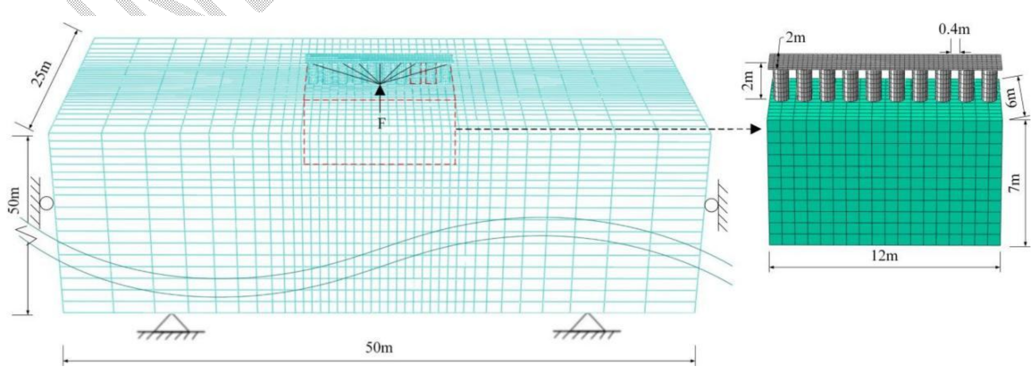


Fig. 4 Mesh generation of finite element model of suction pile dam

For load application, a reference point o is first defined at the top central position of the suction pile dam barrel foundation, as shown in Figure 2. Then the reference point is coupled with the entire pile dam, and the horizontal load is applied to the reference point. When the horizontal displacement reaches the allowable value of the horizontal displacement required by the design, it is considered that the horizontal ultimate bearing capacity of the pile foundation has been reached. In the actual design requirements, the allowable value of the horizontal displacement is generally located at 0.2 times the pile diameter (D), and the pile diameter D of the suction type pile dam is 80cm. The load corresponding to the horizontal displacement of 16cm at the ground is taken as the ultimate horizontal bearing capacity of the suction pile dam. The displacement control method is adopted in the model, and the horizontal displacement x=0.2m is applied at the reference point to explore the influence of subdivision plate on the horizontal bearing performance of the suction pile dam.

3 Analysis of horizontal bearing characteristics

3.1 Determination of loading direction

The direction Angle α is defined as the horizontal Angle between the loading plane and the foundation section, and the loading position is the contact position between the center of the top foundation of the suction pile dam barrel and the mud surface, as shown in Figure 3. In the actual Yellow River environment, suction pile DAMS will be impacted by multiple upward currents, and the horizontal bearing capacity corresponding to different loading directions of pile DAMS will also be different. α is 0° (along pile row direction), 15°, 30°, 45°, 60°, 75°, 90° (perpendicular to pile row direction) to analyze the influence of loading direction. Fig. 5 and Fig. 6 show the horizontal load-displacement curves and the variation curves of the horizontal bearing capacity with the loading Angle under different loading angles. The results show that the horizontal bearing capacity is maximum when the loading Angle is 30° and minimum when the loading Angle is 90°. Combined with the current situation in the actual project, the suction pile dam is more likely to be damaged when it is perpendicular to the downstream flow direction of 90°, so α=90° is used to load in the numerical simulation in this paper.

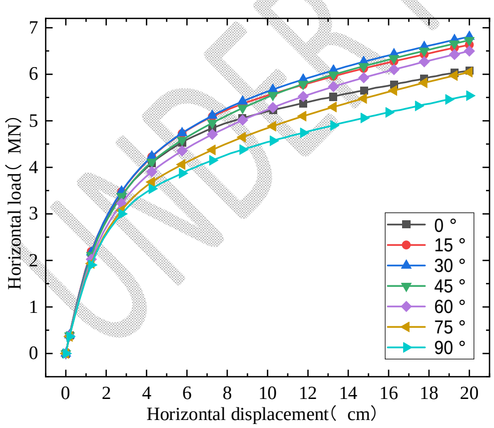


Fig.5 Horizontal load-displacement curves under different loading angles

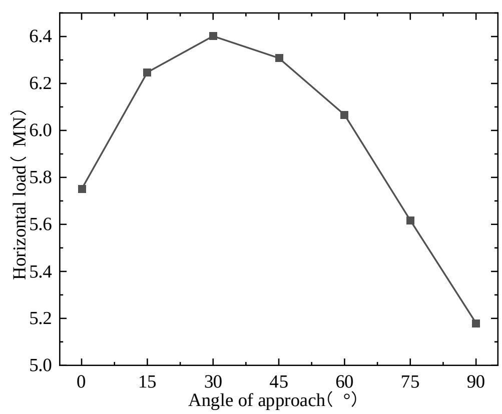


Fig. 6 Curve of horizontal bearing capacity changing with loading angle

3.2 Horizontal ultimate bearing capacity

Fig. 7 and Fig. 8 show the load displacement curve and the change curve of the horizontal bearing capacity of the suction pile dam with the number of subdivision tanks on different barrel bases. It can be seen from the Figure that the ultimate horizontal bearing capacity of the suction pile dam with subdivision plates is significantly higher than that of the single barrel foundation.

The horizontal ultimate bearing capacity of single-barrel, 4-barrel, 6-barrel and 8-barrel suction pile DAMS is 5.18MN, 7.1MN, 7.93MN and 8.33MN, respectively. The horizontal bearing capacity of 4-barrel, 6-barrel and 8-barrel is 37.1%, 53.1% and 60.8% higher than that of single-barrel pile DAMS. The load-displacement curve of suction pile DAMS shows slow deformation without obvious turning point. In other words, the presence of subdivision plates does not change the variation trend of displacement of suction pile with load, and the contact area between cylinder and soil gradually increases with the increase of the number of subdivision tubes in barrel foundation, and the horizontal bearing capacity of suction pile dam with different number of tubes in barrel foundation increases linearly.

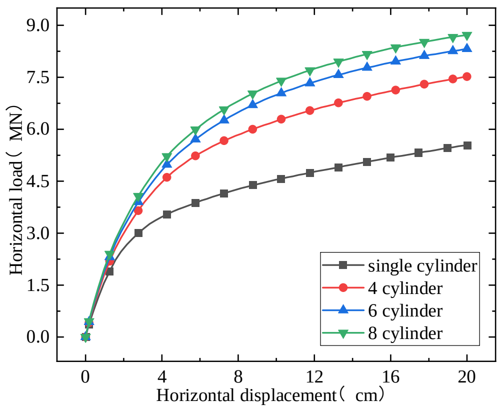


Fig.7 Load-displacement curves under different numbers of buckets of bucket foundation

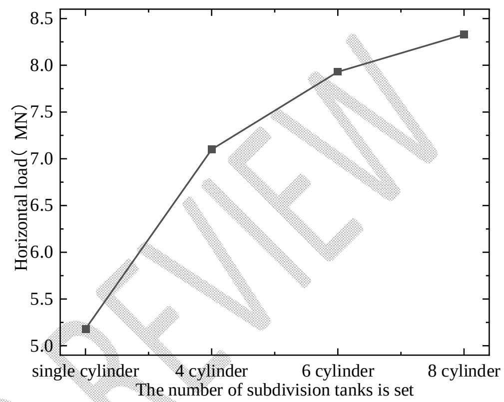
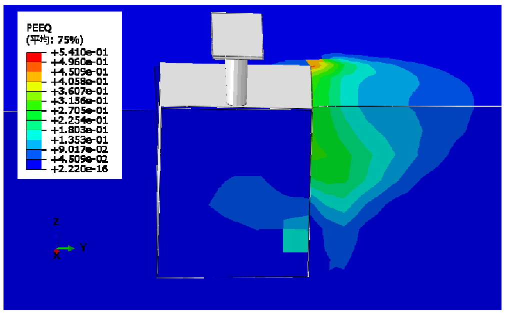
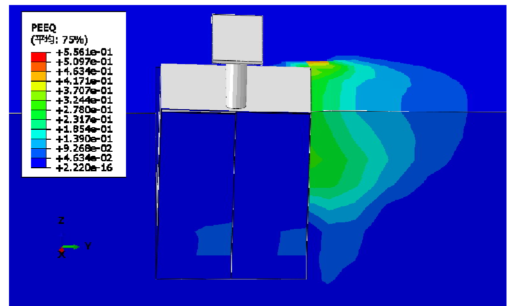


Fig.8 The change curve of horizontal bearing capacity with the setting of subdivision cylinder number

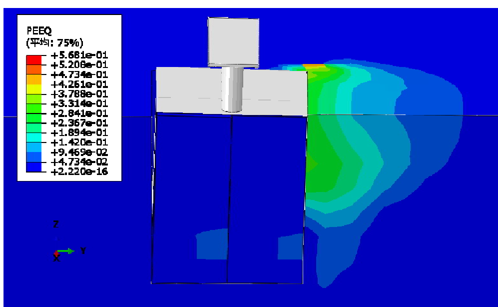
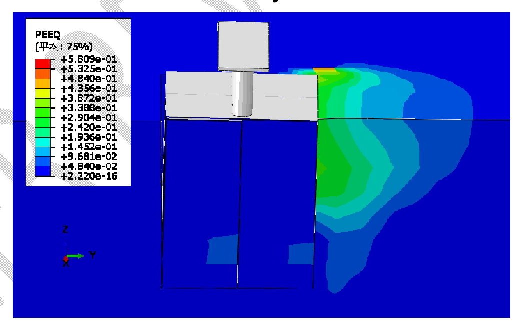
The suction pile dam with subdivision plate is composed of outer cylinder and subdivision plate. Compared with the single suction pile dam, the barrel foundation with subdivision plate has more contact area and higher degree of cooperation with the soil. Under the horizontal limit load, the foundation soil will produce greater soil resistance to the barrel foundation with subdivision plate, so that its horizontal bearing performance can be significantly improved. Therefore, it is necessary to meet the requirements of structural strength, floating and sinking and construction cost, and appropriately increase the number of subdivision barrels to improve the horizontal bearing capacity of suction pile dam in practical engineering.

3.3 Failure mode of cylinder foundation under horizontal ultimate load

Fig. 9 (a) ~ (d) is the equivalent plastic strain diagram of soil under different number of subdivision tubes on the foundation of suction pile dam under horizontal ultimate load. It can be seen from the diagram that under horizontal load, the soil around the foundation forms active and passive soil pressure zones, and most of the upper load is transferred to the passive soil through the interaction between the foundation and the soil. Finally, a wedge-shaped plastic failure zone is formed on one side of the soil in the passive area outside the cylinder. For the suction pile dam without subdivision plate, the plastic zone appears in the soil in the passive zone inside the barrel and the upper side of the passive zone outside the barrel. The failure mode of the other three suction pile DAMS with subdivision plate under horizontal load is similar, and the soil in the barrel has no plastic zone, which is mainly concentrated in the upper side of the passive zone, indicating that the foundation does not occur translational sliding failure, but rotating sliding. With the increase of the number of subdivision tanks, the wedge damage area in the passive area gradually extends below the base of the cylinder and is distributed in an "ear" shape. The local shear failure of passive soil in the cylinder is mainly concentrated in the area around the top cover and the wall of the cylinder. On one side of the active zone outside the barrel foundation, the barrel foundation gradually separates from the foundation soil, resulting in large cracks. The cracks between the single barrel foundation without subdivision plates and the soil foundation appear in the upper part of the barrel foundation, and the barrel foundation has obvious bending points, while the cracks between the multi-barrel foundation and the soil foundation with subdivision plates extend more downward, without obvious bending points.

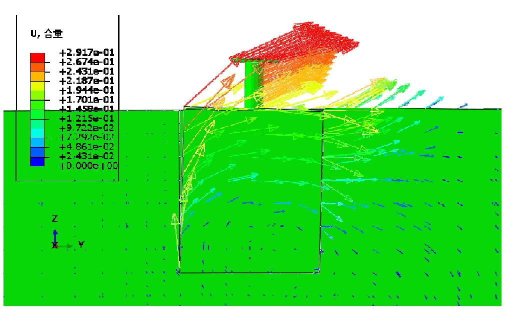
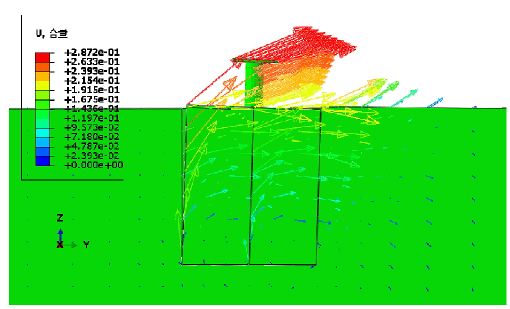
（a）single cylinder （b）4 cylinder

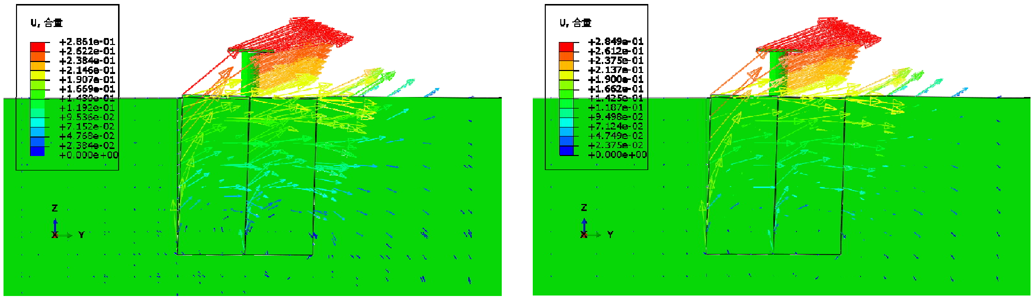
（c）6 cylinder （d）8 cylinder

Fig.9 Equivalent plastic strain cloud diagram of soil under different number of buckets of bucket foundation

Figure 10 (a) ~ (d) below is the horizontal displacement vector diagram of suction pile dam under horizontal ultimate load with different number of subdivision tubes. It can be seen from the diagram that under horizontal ultimate load, soil around the monobar foundation without subdivision plates rotates around the lower center point of the barrel foundation, and the rotation point distribution of the three kinds of multi-barrel foundation with subdivision plates is similar. All of them are distributed in the central axis of the cylinder bottom and the center of the cylinder in the passive area. The rotation trend of multi-barrel foundation with subdivision plate is larger than that of single barrel foundation without subdivision plate, and the horizontal displacement is more obvious.

(a) single cylinder (b) 4 cylinder



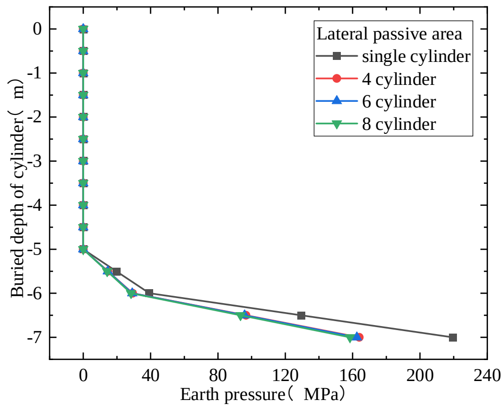
(c) 6 cylinder (d) 8 cylinder

Fig.10 Horizontal displacement vector diagram under the condition of different number of buckets of bucket foundation

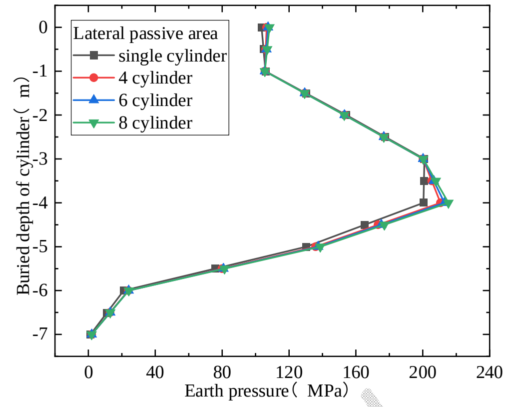
3.4 Soil pressure distribution of cylinder foundation under horizontal ultimate load

Fig. 11 (a) ~ (d) shows the variation curve of soil pressure on the side of the barrel foundation along the buried depth direction of the barrel under the condition of different number of subdivision barrels of the barrel foundation. It can be seen from the Figure that under the action of horizontal ultimate load, nearly half of the earth pressure on the outside of the active zone and the inside of the passive zone of the four kinds of pile DAMS is 0, which indicates that the upper part of the barrel foundation is detached from the soil mass and cracks appear under the action of horizontal ultimate load. After reaching a certain depth (the buried depth of the cylinder foundation is about 4.5m), the pressure begins to increase rapidly, which also indicates that the soil squeezing phenomenon occurs at the bottom of the loading surface of the cylinder foundation. The soil pressure acting on the outside of the passive zone and the inside of the active zone of the barrel foundation increases first and then decreases with the buried depth of the barrel. The main reason is that the compressive strength between the soil in the passive zone and the cylinder wall of the foundation gradually increases, and the value of the earth pressure also increases with the increase of the compressive strength. This indicates that the movement mode of the barrel foundation of the suction pile dam barrel foundation is rotation when it is subjected to the horizontal ultimate load. The soil pressure outside the passive zone and inside the active zone of the barrel foundation presents a parabolic distribution along the direction of the buried depth of the barrel, and the soil pressure outside the active zone and inside the passive zone presents a curved line distribution along the direction of the buried depth of the barrel.

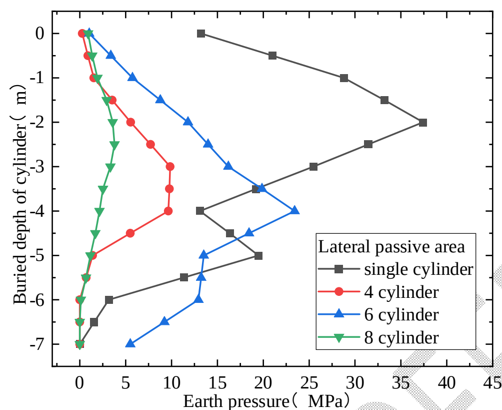
When subjected to the same horizontal displacement, the soil pressure of the multi-barrel foundation outside the active zone is greater than that of the single barrel foundation, but the opposite is true inside the passive zone. The earth pressure outside the passive zone and inside the active zone of the 8-barrel foundation is the smallest, the earth pressure outside the passive zone of the 4-barrel foundation is the largest, and the earth pressure inside the active zone of the single-barrel foundation is the largest. It can be seen that with the increase of the number of subdivision barrels on the barrel foundation, the earth pressure outside the passive zone and inside the active zone of the barrel foundation gradually decreases, indicating that the subdivision plates effectively share the load transferred on the upper part of the barrel foundation. The cooperation degree of tube-soil in the foundation of suction pile dam barrel is improved, and the compressive strength between tube-soil in the passive area is reduced, that is, the horizontal displacement of suction pile dam under horizontal load is reduced.



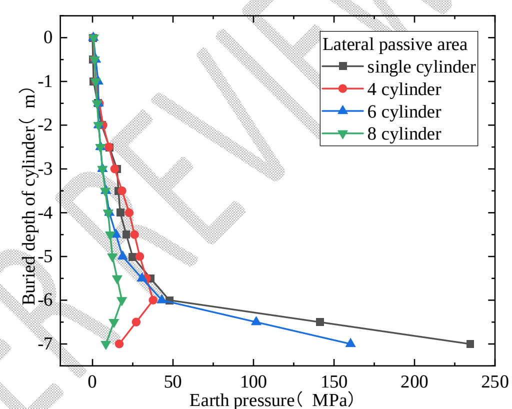
（a）The distribution curve of soil pressure outside the active zone



（b）The distribution curve of soil pressure outside the passive zone



（c）The distribution curve of soil pressure inside the active zone



（d）The distribution curve of soil pressure inside the passive zone

Fig.11 The distribution curve of earth pressure on the side wall of the bucket foundation under different numbers of buckets

4 Conclusion

The numerical model of suction pile dam is established, and the influence of the number of subdivision tanks on the horizontal bearing characteristics of suction pile dam is discussed. The following conclusions are drawn:

(1) With the increase of the number of subdivision barrels in the barrel foundation, the contact area between the cylinder and soil gradually increases, and the horizontal bearing capacity of the suction pile dam with different number of subdivision barrels increases linearly. The horizontal bearing capacity of the suction pile dam with 4, 6 and 8 barrels increases by 37.1%, 53.1% and 60.8% compared with that of the single barrel.

(2) Under the horizontal limit load, the plastic failure zone is mainly distributed on the soil side of the passive zone, forming a wedge-shaped plastic failure zone. With the increase of the number of subdivision tanks, the wedge failure zone in the passive zone gradually extends to the soil under the foundation, forming an "ear" -shaped distribution. On the active zone side, the foundation of the cylinder is separated from the foundation soil, resulting in large cracks. The rotation trend of multi-barrel foundation with subdivision plate is larger than that of single barrel

foundation without subdivision plate, and the horizontal displacement is more obvious.

(3) The earth pressure in the passive region plays a major role in the horizontal load bearing of the barrel foundation. With the increase of the number of subdivision cylinders in the barrel foundation, the earth pressure on the outside of the passive region and the inside of the active region of the barrel foundation gradually decreases, indicating that the subdivision plates effectively share the load transferred from the upper part of the barrel foundation, improve the cooperation-soil degree in the barrel foundation of suction pile dam, and reduce the compressive strength between the tubes and soil in the passive region.

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