Mechanical properties of a new string capsule drainage anchor and its supporting effect in deep foundation pit

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Abstract. With the increase of the scale and depth of urban underground space construction in coastal soft soil area, the traditional anchoring technology has been difficult to meet the requirements of deep foundation pit excavation and support. This paper puts forward a new type of string capsule drainage anchor supporting structure, introduces its structure composition, analyzes its working mechanism and mechanical characteristics, the calculation formula of ultimate bearing capacity of small cylindrical shear failure between anchor and surrounding soil is given, finally, the supporting effect of the new structure in deep foundation pit engineering is simulated and analyzed by finite element software. It is concluded that the stress of the new type of anchor can be divided into three stages: static earth pressure, plastic zone development and plastic zone breaks through; the new anchor can quickly dissipate the pore water pressure in the surrounding soil, which is more conducive to the stability of foundation pit; the axial force distribution presents a "sawtooth" shape, and the axial force increases sharply in the expanding section; the supporting effect of the new anchor is more obvious than that of the traditional anchor, which can more effectively inhibit the horizontal displacement of the slope.

1. Introduction
With the increase of the scale and depth of urban underground space construction in coastal soft soil area, the problem of foundation pit safety has become increasingly prominent, and the traditional anchor support structure has been unable to meet the requirements of deep foundation pit excavation support, for example, the grouting anchor[1] has some problems, such as difficult hole forming and slow increase of grouting strength; the self drilling anchor[2] has some problems, such as unsatisfactory anchoring effect, the practice shows that the anchor has "effective length", and unlimited increase of anchor length can not effectively improve the anchoring force.

At present, the expansion anchor technology is widely concerned by professionals due to its high bearing capacity, according to the different expansion types, the expansion anchor can be divided into expansion grouting type[3], inflation expansion type[4-5], pretension (compression) expansion type[6], etc. The practice shows that: the expansion grouting anchor has some problems, such as difficult hole forming, poor integrity of expansion section and rod body; the inflatable expansion anchor is still in the development stage, and the air bag strength and applicability are uncertain; the construction of
preloading (tension) expansion anchor is simple, however, due to the complex structure and high production cost, it is difficult to get large-scale application in engineering. The stability of foundation pit should not be limited to the improvement of supporting structure, dewatering design before or during foundation pit excavation is also important, at present, well point method and slope intubation method are widely used in foundation pit dewatering[7], the drainage effect of well point method is obvious, but the construction technology is complicated and needs vacuum pumping; the drainage effect of intubation method for deep soil is not obvious.

The new type of string capsule drainage anchor is a new support structure which integrates drainage[8] and expansion anchorage technology[9]. In terms of structure type, the expansion section absorbs water and expands to form the anchorage expansion end, combined with the frame retaining wall, the potential sliding soil is anchored in the surrounding stable soil layer; in terms of drainage, the anchor rod provides an ideal drainage channel for the slope, which can effectively accelerate the consolidation rate of soft soil. At present, the mechanical characteristics and supporting effect of the new structure are not clear, and the structural design is not perfect, in order to guide the subsequent design and construction, it is urgent to carry out in-depth research.

2. Structure composition of string capsule type drainage anchor
The structure of string capsule type drainage anchor is composed of drill bit, expansion ring, filter pipe and steel pipe. The drill bit is equipped with twisted blade, and the expansion ring is made of high strength water absorption and expansion rubber material, which is fixed around the steel pipe, the water filtering hole is set on the water filtering pipe, and the unidirectional permeable membrane is bound on the surface. The structural diagram of the self draining series expansion anchor is shown in Figure 1. The self draining series expansion anchor is fixedly connected with the lattice retaining wall through the anchorage and steel backing plate, and cooperates with the retaining plate to bear the earth pressure. The overall structure section is shown in Figure 2.

![Figure 1. Structural diagram of string capsule drainage anchor.](image1)

![Figure 2. Application effect of string bag drainage anchor.](image2)
3. Mechanical characteristics and bearing capacity calculation of string capsule drainage anchor

3.1. Analysis of mechanical characteristics
Along with the excavation process of foundation pit, the mechanical characteristics of string capsule drainage anchor can be divided into three stages:

Static earth pressure stage. In the initial stage of foundation pit excavation, the horizontal displacement of slope is small, and there is no relative displacement between the anchor and the surrounding soil, the anchor tension mainly includes the side friction of expansion body and the rod, and the front face of the expansion body is subjected to static earth pressure.

Plastic zone development stage. With the increase of excavation depth, the horizontal displacement of slope gradually increases, the relative displacement between soil and anchor occurs, the side friction changes from static friction to sliding friction, the front face of expansion body bears soil pressure, the end resistance increases gradually, the local plastic zone gradually appears at the front face of the expansion body due to the soil compression.

Breakthrough stage. With the increase of slope displacement, the external load tension of the anchor continues to increase, and each expansion section plays the role of anchoring. The plastic zone of the soil at the front end of the expansion body continues to expand forward, because the soil in the plastic zone is constrained by the overlying soil, when the end resistance increases to a certain extent, the plastic zone between adjacent expansion bodies will be broken through.

3.2. Calculation of ultimate bearing capacity
Through the analysis of the mechanical characteristics of the string capsule drainage anchor, it can be seen that the bearing capacity is mainly composed of the front end resistance of the expansion body, the side friction resistance of the expansion body and the rod body. If the soil around the anchor is considered as a small cylindrical shear failure and the dissipation of pore water pressure is considered, the ultimate bearing capacity is calculated as follows:

The resistance of the front end face of the expansion body is:

\[ Q_f = \beta \mu (p_u - u_w + \Delta \sigma_r) \frac{\pi (D_e^2 - d^2)}{4} \]  

\( Q_f \), the end resistance of the expanding body in the case of small cylindrical surface failure; \( \beta \), the end resistance correction coefficient, which is 4.5-6.5 for temporary anchor and 3.0-5.0 \[^{[10]}\] for permanent anchor; \( p_u \), the expansion pressure; \( \mu \), the friction coefficient between the expansion body and soil; \( u_w \), the pore water pressure, for saturated soil, \( u_w = \Delta u_{sat} \); \( \Delta \sigma_r \), the radial stress increment on the expanding side; \( d \), the rod diameter; \( D_e \), the equivalent diameter of the expanded body.

The side resistance of expansion is:

\[ Q_{L1} = \pi D_e L_e \left[ c + (P_u - u_w) \tan \varphi \right] \]  

\( Q_{L1} \), the side resistance of the expansion body; \( L_e \), the effective length of the friction section of the expansion body, \( L_e = 0.7 L - 0.9 L \[^{[5]}\] \); \( L \), the expansion body length; \( c \), the cohesion; \( \sigma_{ra} \), the radial effective stress of the expansion body, \( \sigma_{ra} = p_u - u_w \); \( \varphi \), the internal friction angle.

The side resistance of rod is:

\[ Q_{L2} = \pi d L_j \left[ c + K_u (\sigma - u_w) \tan \varphi \right] \]  

\( Q_{L2} \), the side resistance of the rod body; \( L_j \), the length of the friction section of the rod body; \( K_u \), the coefficient of lateral earth pressure; \( \sigma \), the average stress of the soil on the side of the rod body, \( \sigma = \gamma_{sat} H \); \( \gamma_{sat} \), the saturated soil weight, \( H \), the average thickness of the soil over the rod.

The ultimate uplift bearing capacity is:
4. Simulation of excavation support and drainage process of deep foundation pit

4.1. Establishment of finite element model

A two-dimensional solid model of foundation pit is established for supporting and drainage simulation. The model size is 60m×40m, the excavation depth of foundation pit is 10m, and the slope angle is 80°. Three layers of anchor are used for supporting, the vertical distance between the first layer of anchor and the top of slope is 3.5m, and the vertical distance between each layer of anchor is 2.0m. The length of the first layer anchor is 8m, three expansion rings are set on the rod body at the anchorage end, the length of the second layer anchor is 6.6m, two expansion rings are set, the length of the third layer anchor is 5.0m, one expansion ring is set, the length of expansion ring is 0.6m, the length of the filter pipe is 0.8m, and the thickness of the frame retaining wall is 400mm. The parameters of soil layer and anchor rod are shown in Table 1.

| Name       | Density (kN/m³) | Poisson's ratio | Cohesion c (kPa) | Internal friction angle \(\varphi(°)\) |
|------------|----------------|----------------|------------------|-------------------------------|
| Soil layer |                |                |                  |                               |
| Silty clay | 19             | 0.3            | 5                | 16                            |
| Silt       | 20             | 0.3            | -                | 27                            |
| Clay       | 16             | 0.3            | 12               | 3                             |
| Anchor     |                |                |                  |                               |
| Rod body   | 78             | 0.2            | -                | -                             |
| Expansion ring | 30     | 0.35          | -                | -                             |

Mohr-Coulomb elastic-plastic model is used for soil; linear elastic model is used for frame retaining wall and anchor. The rod, the expansion ring and the filter pipe are set as rebar units with variable cross-section, the sectional area of the rod body and the filter pipe is 12.56×10⁻⁴m², and the cross-sectional area of the water absorption expansion ring is 3.14×10⁻²m²; the beam element is used for the frame retaining wall, the porous medium property of aquifer soil is given, and the filter pipe is set as the drainage boundary. The finite element model is shown in Figure 3.

Figure 3. Finite element meshes.

4.2. Simulation of excavation support and drainage process of foundation pit

The excavation and support is realized by the function of unit life and death, and the drainage process is reflected by the dissipation of pore water pressure, the detailed steps are as follows:

1. Element division: anchor element, frame retaining wall element and soil element are divided, and each element is defined as soil material property;
2. Aquifer soil simulation, giving each soil layer unit porous media properties;
3. Excavation simulation; “kill” the soil element of the first layer excavation;
(4) Drainage simulation: the anchor filter pipe is set as the drainage boundary;
(5) Support simulation: the properties of soil parameters at the support structure are modified to the material parameters of the support structure;
(6) Repeat steps (3) to (5) until the excavation reaches the design elevation.

4.3. Analysis of calculation results

4.3.1. Analysis of drainage effect
Figure 4 shows the pore water pressure distribution in 2 days and 4 days after the completion of the excavation. It can be seen that the string capsule drainage anchor can effectively eliminate the excess pore water pressure in a short time, after 4 days of excavation, the excess pore water pressure in the slope surface has basically dissipated. Therefore, the string capsule drainage anchor has good drainage effect, and can quickly dissipate the pore water pressure in a short time.

![Figure 4. Diagram of pore water pressure.](image)

4.3.2. Analysis of support effect
In order to clearly understand the supporting effect of the string capsule drainage anchor, the results of the model and the ordinary anchor support model are compared and analyzed.

(1) Analysis of axial force
Figure 5 shows the axial force distribution nephogram of the string capsule drainage anchor and ordinary anchor after the whole excavation and support of the foundation pit. It can be seen from the figure that the axial force distribution of the string capsule drainage anchor is quite different from that of the ordinary anchor, the maximum axial force of the ordinary anchor is near the slope, and the axial force of the string capsule drainage anchor rises sharply at the position of the water absorption expansion ring, and the axial force distribution presents a "sawtooth" shape, the axial force distribution of the rod is obviously smaller than that of the ordinary anchor. This is due to the foundation pit excavation unloading, the soil behind the slope produces horizontal displacement, the frame retaining wall bears the active earth pressure, pulling the anchor to move into the pit, and most of the tensile force is transferred to the stable soil layer in the anchorage zone in the form of end resistance and side friction by the water absorption expansion ring, while the ordinary anchor mainly bears the tensile force in the form of side friction.

![Figure 5. Diagram of anchor axial force (unit: N).](image)
(2) Horizontal displacement analysis of frame retaining wall

Figure 6 shows the horizontal displacement distribution curve of the frame retaining wall under the support of string capsule drainage anchor and ordinary anchor. The horizontal displacement of frame retaining wall is "convex belly" distribution under the action of two kinds of supporting structures, and the maximum displacement is near the bottom of the pit, while the support effect of string capsule drainage anchor is more obvious, which can effectively protect the foundation pit reducing the horizontal displacement, its more conducive to the stability of foundation pit.

Figure 6. Horizontal displacement of grillage retaining wall.

5. Conclusion

(1) Along with the excavation process of foundation pit, the mechanical characteristics of string capsule drainage anchor can be divided into three stages: static earth pressure stage, plastic zone development stage and plastic zone through failure stage, the calculation formula of ultimate bearing capacity of small cylindrical shear failure between anchor and surrounding soil is given.

(2) The string capsule drainage anchor has good drainage effect, which can quickly dissipate the pore water pressure in the soil, and can effectively improve the stability of the foundation pit.

(3) Different from the mechanical characteristics of ordinary anchor structure, the axial force of string capsule drainage anchor rises sharply in the expansion section, while the axial force distribution of the rod body is obviously smaller than that of ordinary anchor, the axial force distribution presents a "sawtooth" shape.

(4) Compared with the ordinary frame anchor support structure, the effect of string capsule drainage anchor support is more obvious, and it can reduce the horizontal displacement of foundation pit in the process of foundation pit excavation.

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