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Research on Bearing Capacity Calculation Method of Large Diameter Cylinder in Soft Clay

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Abstract A large diameter cylinder inserted in soils is a new type of engineering structures used in offshore and port engineering. The mechanism of its bearing capacity and the analysis of its stability are important to its design and applications. In this paper, the finite element method is used to analyze the reacting forces of the soft soil foundation on the structure under the wave action. A simplified method is proposed, based on the plastic limit method, for the safety and stability analysis. Our analysis shows that the assumptions made in this paper and the mechanism used are reasonable, and the results obtained are appropriate. The calculation method is very efficient and can be used to evaluate main parameters of the structure in its preliminary designs.

Keywords: Limit equilibrium, cylinder of large diameter, soft clay, stability, finite element method

INTRODUCTION

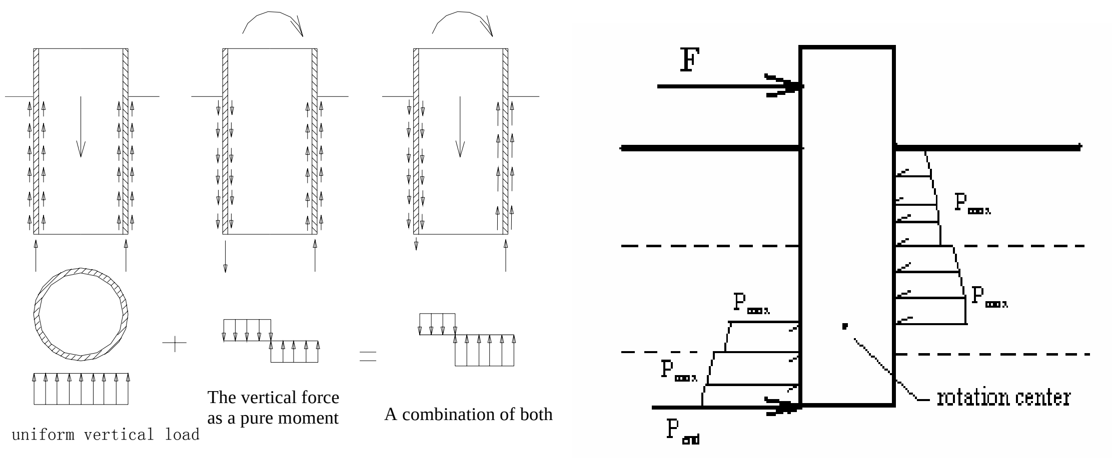
A large diameter cylinder inserted in soils is a new type of engineering structures used in offshore and port engineering. It is a thin-walled cylinder made of steel or reinforced concrete, without cover and bottom. A chain of such structures aligned in a line can form a band structure to serve as a retaining wall in a port, as well as a guide dam or a breakwater, with a great potential for their applications in port engineering. According to the manners of how it is embedded in soils, the structure can be classified into three types: the foundation type, the shallow-rooted type and the deep-rooted type[1]. There have already been a number of studies on its deformations, internal stresses, stability analysis, interactions between the structure and soils, etc., which have greatly promoted its applications[1-4]. But the mechanism of its bearing capacity remains to be further explored, and there are still rooms for improving the calculation methods for its stability analysis. Previous attentions are mainly focused on the structures of the foundation type and the shallow-rooted type, which mainly serve as retaining walls, the studies on the deep-rooted type are relatively few.

For the NIIC segment of the north guide dike in the deep water passage at the mouth of Yangtze River, a surface layer of about 30m of the foundation is composed mainly of muck or mucky clay, with very low undrained strength. Therefore it is recommended to use the structures of cylinders of large diameter of deep-rooted type in the preliminary design. The four cylinders of 12 m in diameter used in the test segment were capsized during the typhoon Rammasun in early July, 2002, which have provided some precious information for the studies of cylinders of large diameter of deep-rooted type and been studied by many experts and scientific research institutions.

In this paper, a calculation method is proposed for analyzing the bearing capacity of a cylinder of this type in soft soils foundation, based on the plastic limit analysis. This method has already been put into use in the preliminary design of the NIIC segment of the north guide dike in the deep water passage at the mouth of Yangtze River. In the meantime, the finite element analysis software ABAQUS is used to calculate the deformations of the cylinder under the action of wave loading, which has verified the validity of the method.

MECHANISM OF BEARING CAPACITY AND THEORETICAL FOUNDATION FOR THE CALCULATION METHOD

The loads on the cylinder of large diameter of deep-rooted type used as a guide dike come mostly from waves and currents. Under the action of the horizontal and vertical loading on its top parts, the structure will subside, translate and rotate. As shown in Fig.1(a), under the action of the axial vertical loading, the soil will exert an upward friction on the cylinder along the wall both inside and outside the cylinder and will produce a vertical end reacting force on the cylinder annulus. Due to the rotation of the cylinder, the vertical reacting force will adjust itself to bear some bending moments. The translation and rotation of the cylinder will jointly push a wedge of soil block under the soil surface as if ploughing through the soil. The distribution of the horizontal reacting force is shown in Fig. 1(b). In the following sections we will describe the calculation methods of the ultimate bearing forces.



(a) *(b)*

Fig. 1. A Sketch of the Distribution Vertical and Horizontal Reacting Force on a Cylinder

1. Vertical bearing force For a soft clay ground, if the load is transient or its duration is short, the soil block will not have enough time to be drained and consolidated, therefore, it would be appropriate to use the undrained shear strength in the analysis.

For the vertical bearing force, one may use the α method quoted by API[5], that is, the vertical bearing force, Q_d, is the sum of the friction on the side of the cylinder, Q_f, and the reacting force at the end, Q_p:

$$Q_d = Q_f + Q_p = fA_s + qA_p \tag{1}$$

$$f = \alpha c_u \tag{2}$$

where f is the friction on the side of the cylinder per unit area, c_u is the undrained shear strength at the calculation point, A_s is the total area comprising the inner and outer walls of the cylinder inside the soils, q is the reacting force at the end per unit area, A_p is the area at the end of the cylinder. α is a non-dimensional factor, to be determined by Eq. (3), and $\alpha \le 1$.

$$\begin{aligned} \alpha &= 0.5\psi^{-0.5} \qquad \psi \le 1.0 \\ \alpha &= 0.5\psi^{-0.25} \qquad \psi > 1.0 \end{aligned} \tag{3}$$

where $\psi = c_u / \sigma_z$,σ_z is the effective vertical stress at the point in question.

$$q = 9c_u \tag{4}$$

2. Horizontal bearing force The plastic limit analysis method is used for the calculation of the horizontal bearing force. As shown in Fig. 1(b), if the rotation center is located on the axis of the cylinder under the mudline, the horizontal reacting force of the cylinder is the sum of the horizontal reacting force directly acting on the side of the cylinder and the friction at the end of the cylinder. The ultimate reacting force of the cylinder can be obtained by equilibrium conditions of forces and moments.

The key part of the calculation is to determine the ultimate horizontal reacting force per unit area. According to a three dimensional plastic limit analysis, our problem can be reduced to a two dimensional calculation scheme and the reacting force of the soil per unit area can be calculated as follows[6,7,8].

For a clay ground, if the side of the cylinder that tends to separate from the soil block is cracked under a load, the average ultimate reacting force of the soil block on the side of the cylinder per unit area at the depth of z can be calculated as:

$$P_{\max} = N_p c_u + \sigma_z \tag{5}$$

where σ_z is the vertical effective compressive stress in the soil block at the acting point, N_p is a non-dimensional force bearing factor.

In a section of a soil block of single layer, the strength of the soil at the surface is S_{u0}, which will increase linearly with the depth at a rate of S_{u1}. The following empirical relation can be used:

$$N_p = N_1 - N_2 \exp(-\frac{\xi z}{D}) \tag{6}$$

where D is the diameter of the cylinder, z is the depth, N_1 and N_2 are parameters related to the roughness of the cylinder's surface. Considering the cyclic wave loading on the cylinder, which is taken as a smooth pile, according to the plastic limit analysis, taking $N_1=9$ and $N_2=7$, we have

$$\begin{aligned} &\xi = 0.25 + 0.05\lambda \qquad \lambda < 6 \\ &\xi = 0.55 \qquad\qquad\quad \lambda \ge 6 \end{aligned} \tag{7}$$

where $\lambda = s_{u0} /(s_{u1} D)$.

The total horizontal reacting force inside the cylinder and at the tip can be approximately calculated as half of the ultimate shear resistance at the tip plane of the cylinder:

$$p_{end} = 0.5 c_u A_{end} \tag{8}$$

where A_{end} is the area of the end of the cylinder, encircled by its outer wall.

For soil blocks with layers, the following approximation is used. In calculating the ultimate horizontal reacting force of the layer just beneath the surface layer, a modified depth value will be used as z in Eq. (6), taking account of the parameters and a reduced thickness of the covering layer.

3. Vertical bearing moment When the ratio of the vertical ultimate bearing capacity over the load is more than that of the horizontal one, the vertical reacting force should be adjusted to balance a part of the bending moment, to simulate the mechanism of the bending moment being jointly balanced by the vertical and horizontal forces. As a final result, the values of both ratios should be equal, which is the overall safety factor under the designed load. Since the equilibrium conditions are satisfied in the calculation of the horizontal and vertical bearing forces, the adjustment in the balance of moments should be done through iterations.

Under the rotation action, part of the left side of the cylinder in Fig. 1(a) may be acted by a downward friction. But due to the cracking between the soils and the cylinder, the related friction will vanish, so in the calculation of the total friction of this portion, it is necessary to use a reduction factor for the total opposite direction friction, which is taken as 0.2 in this paper. In the clay ground, the end of the cylinder will have a force of suction during the rotation and there will be a reacting force of the same magnitude acting at the end when it moves upward.

For aligned chained cylinders, the interactions between neighboring cylinders should also be considered. A reduction factor will be used to calculate the vertical and the horizontal bearing force, depending on the space between neighboring cylinders. In the calculation of the lateral bearing capacity, the lateral force on the side of cylinder per unit depth might not be greater than the passive soil pressure acted on a vertical wall per unit depth obtained according to the Rankine soil pressure theory.

The above algorism is incorporated into a special program CYLINDER for the stability calculation of cylinders of large diameter.

FINITE ELEMENT METHOD CALCULATION

ABAQUS is used for the finite element calculation, as it enjoys a very good capacity for handling nonlinear problems and has been found wide applications in the rock and soil engineering fields. The three dimensional deformations and stresses are calculated for a single cylinder in a soil block. The contact between the cylinder and the soil block is handled by the frictional contact pair provided by ABAQUS. The contact in the normal direction is treated as a 'hard contact', that is, the two bodies in contact will not immerse one another under a normal compression, but will separate under a normal tension; the contact in the tangent direction is treated as a frictional contact controlled through friction coefficients. The linear elastic constitutive relations and the elastic-Tresca ideal plastic relations are used for the cylinder and the soil block, respectively. The calculation is carried out in a large deformation and static mode.

The main parameters used in the calculations are as follows: the outer diameter of the cylinder is 12.0 m, the wall thickness above the mudline 0.25 m, the wall thickness two meters below the mudline 0.21 m, (in between them is a transition segment), and the dead weight of the top breastwork of the cylinder under water 2822 kN. During the typhoon Rammasun, the wave height of 1% cumulative frequency is 7.39m, from which the horizontal wave force acted on the structure is obtained as 7066.2 kN, the vertical wave force as 3561.3 kN, and the bending moment at mudline as 32858 kNm, calculated according to the Chinese Code of hydrology for Sea Harbour declared in 1998.

The soil layers parameters listed in Table 1 are used in the calculation. Considering the undrained shear strength of the soil, the internal friction angle for consolidation quick shear and the reduction of friction at the contact surface, the friction coefficient on the contact surface is taken as 0.20, under the constraint that the maximum friction force may not exceed 25 kPa.

Table 1. Soil Layer Parameters for Design

Depth of soil layer	0-5.5m	5.5-9.5m	9.5-13.8m	13.8-30m
effective weight (kN/m^3)	6.0	6.6	6.9	6.9
Shear strength (kPa)	10.7	17.0	23.3	23.3
Poisson's ratio	0.49	0.49	0.49	0.49
Deformation modulus (MPa)	1.5	1.5	1.5	1.5

Fig. 2 gives the curve of the horizontal force versus horizontal displacement at mudline for a single cylinder when the load is applied proportionally according to Rammasun wave. From the curve, the ultimate horizontal bearing force may be estimated as a little bit greater than 6000 kN.

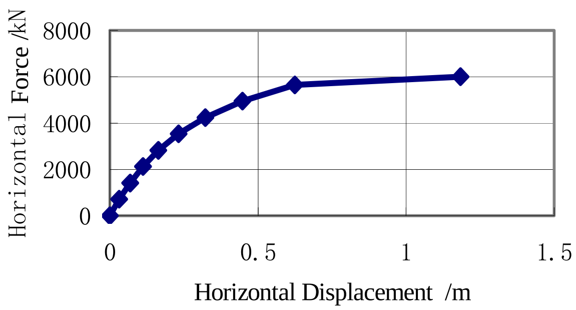
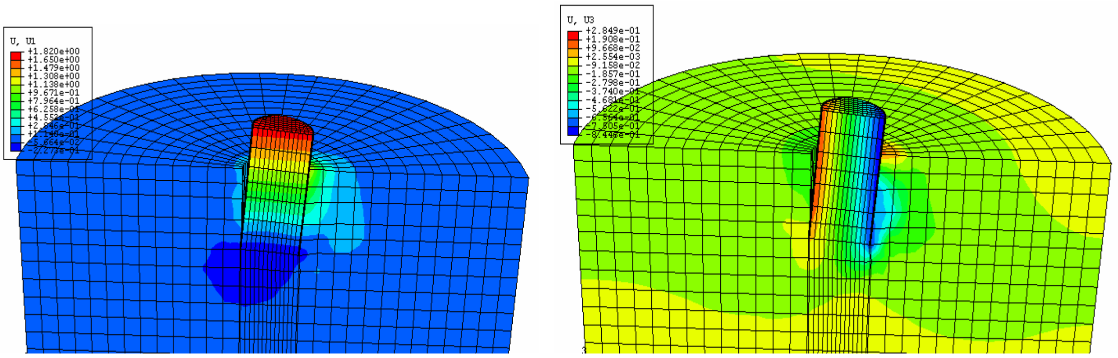


Fig. 2. Horizontal Force Versus Displacement Curve for a Single Cylinder Under Rammasun Wave Loading

Figs. 3 gives contours of horizontal and vertical displacements under a horizontal force of 6000 kN. It can be seen from the Fig.s that the cylinder undergoes a capsizing rotation, with the rotation center near the end of the cylinder and one side of the cylinder is cracked. The cylinder end and the part of soil block at the cracking side move upward, and the surface of the soil block at the other side bulges, which verifies the assumptions adopted in the method mentioned above.



(a) *(b)*

Fig. 3 Contours of Lateral (a) and Vertical (b) Displacements under a Horizontal Force of 6000 Kn

Fig. 4 gives the distribution of the horizontal reacting force in the soil along the depth of the cylinder under a horizontal force of 4200 kN which equals 70% of the ultimate bearing capacity. The horizontal reacting force is the sum of the projections of the normal and shear stresses in the cylinder’s periphery. It can be seen from the Fig. that there exists a switch point on the curve where the reacting force changes its direction and there is a relatively large resultant reacting force on the side of the soil block that the cylinder moves toward. Due to the geometrical feature of the cylinder, the horizontal shear forces on to the cylinder are in the opposite direction as the movement of the cylinder, therefore, the resultant horizontal reacting forces on both sides of the cylinder are in the same direction, unlike the case of a wall. Generally speaking, the distributions of horizontal reacting forces agree quite well with those obtained by the plastic limit analysis. Because the soil block in the cylinder is constrained by the cylinder, the resultant horizontal reacting force is mostly equal to zero, except near the tip of the cylinder, where due to the shear induced by the rotation, it does not vanish altogether. That phenomenon is also observed in the plastic limit analysis.
Fig. 5 gives the distribution of the vertical friction force on the side of the cylinder. According to the frictional contact mode used in the calculation, the friction force is proportional to the normal stress on the contact surface, in the opposite direction as the movement of the cylinder relative to the soil block. It can be seen from the Fig. that the outside friction forces above and below the switch point are in opposite directions, which shows that it is reasonable to adjust the direction of the friction force to balance the bending moment, as is done in the program CYLINDER. With the undrained clays, the calculation method proposed in API is more reasonable for the contact friction force, as is adopted by the program CYLINDER.

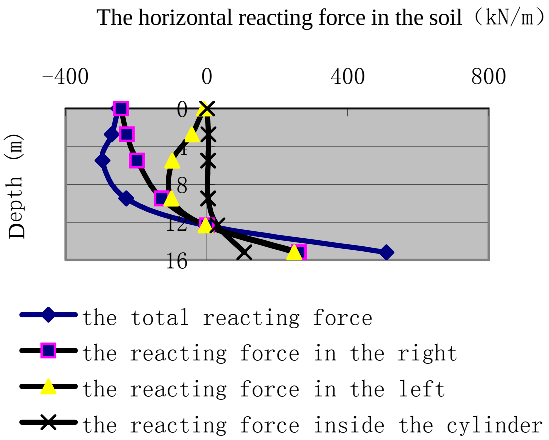


Fig. 4. The Distribution of The Horizontal Reacting Force in Soils Along the Depth of the Cylinder

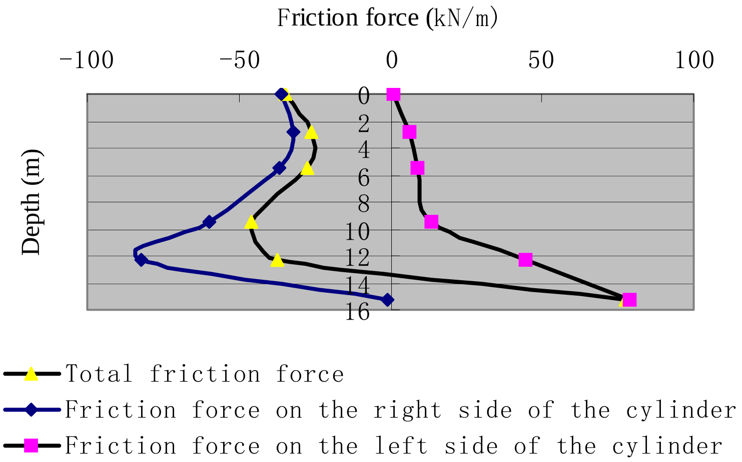


Fig. 5. The Distribution of The Friction Force on the Side of the Cylinder

Fig. 8 gives the distribution of the vertical reacting force and the horizontal shear force at the tip of the cylinder. From the Fig., it is seen that the vertical reacting force and the horizontal shear force on some part are equal to zero due to the separation of the contact surfaces. On the other part, the vertical reacting force varies approximately linearly. On that Fig., the reacting force at the outside rim of the tip is much larger than that at the inside rim, it can be explained by the difference of the strains of related soil blocks. The fact that the tip of the cylinder and the soil block are in a rigid contact is also reflected in that Fig.. The soil block might undergo a very large deformation at that part, where the finite element calculation may fails to give correct results locally. The distribution of the vertical reacting force shows that it does balance some of the capsizing moment on the cylinder. The horizontal shear stresses reach its extreme at the outside rim, and it doesn't at the inside rim.

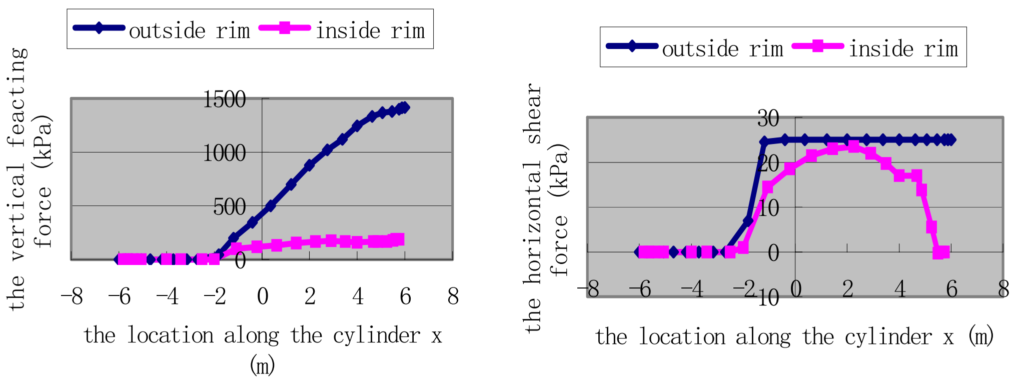


Fig. 8. Distribution of the Vertical Reacting Force and the Horizontal Shear Force at the Tip of The Cylinder

With the same strength parameters, the program CYLINDER is used to calculate the ultimate horizontal bearing capacity for a single cylinder. It is 3842 kN before the vertical reacting force is adjusted to balance a part of the bending moment, and is 6112 kN after the adjustment, which agrees fairly well with the finite element result. The difference of the ultimate bearing capacity before and after adjustment shows that it is important to consider the effect of the vertical reacting force in balancing the bending moment on the horizontal bearing capacity, and for the cylinder of large diameter of deep-rooted type, which bears the vertical loads mainly through the friction on the side of the cylinder, the reduction of the vertical loads may enhance the overall bearing capacity of the structure, unlike the cylinders of foundation type and shallow-rooted type, which bear the vertical loads mainly through the reacting force at the end of the cylinder.

CONCLUSIONS

The following conclusions can be reached through the above analyses:

The assumptions and failure mechanisms used in the calculation methods for the ultimate bearing capacity of cylinders of large diameter of the deep-rooted type proposed in this paper are verified by the results of the finite element analysis. It is reasonable to let the vertical and horizontal reacting forces to balance the bending moment jointly. The results obtained here are appropriate.

It should be mentioned that under the action of dynamic cyclic wave loading, the soils may be softened with a declining strength, which may influence the ultimate bearing capacity. That effect has not been discussed in this paper.

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