H_c ,the horizontal earth pressure behind the pile is reduce, while the horizontal earth pressure before the pile is increase, the distribution of side earth pressure of pile is shown in Fig.8(b), the friction increment due to earth pressure increment +△σh is smaller than the friction reducement due to earth pressure reducement -△σh, on the other hand, the bottom of belled pile emerge small rotary, therefore, side friction resistance of pile V_s is reduce, the resistance at the bottom of belled pile V_b is increase, when horizontal load H is bigger than H_c, as the pile has larger rotation, contact between the bottom of belled pile and foundation become looser, the horizontal earth pressure behind the pile and the horizontal earth pressure before the pile is become bigger, V_s increase, V_b is reduce, the distribution of side earth pressure of pile is shown in Fig.8(c).

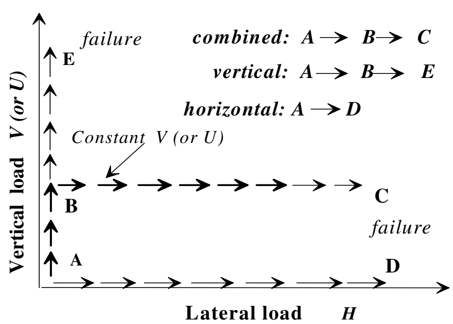


Fig. 4. Loading path

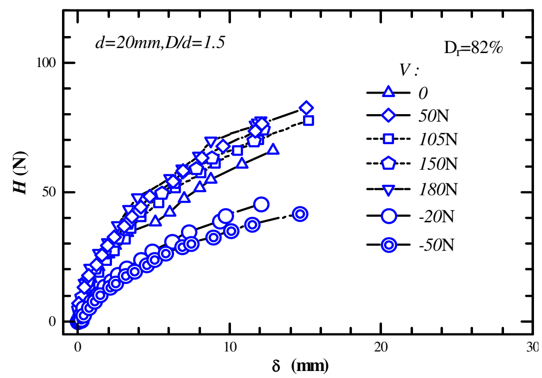


Fig. 5. The H - δ curves in different V

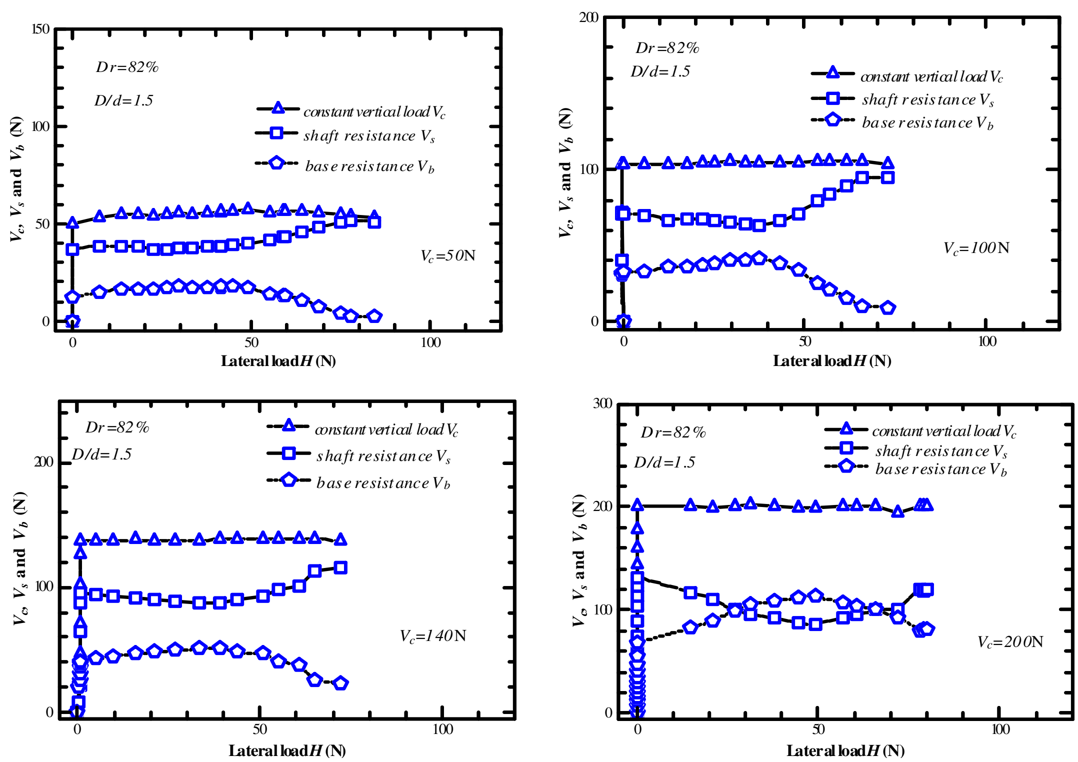


Fig. 6. The variations of Vc Vs and Vb with the increase of lateral load

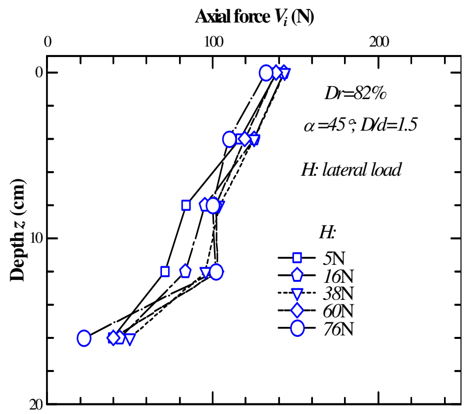


Fig.7 The variation of axial force distribution during lateral loading

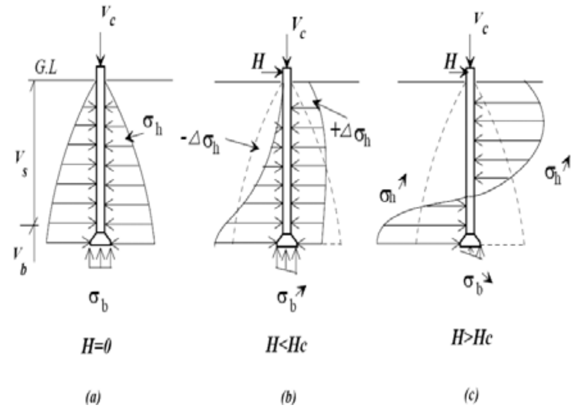


Fig.8 Variations of horizontal soil stress around pile with the increase of H at V_c

Yield envelope curve under the effects of vertical load and horizontal load

Fig.5 is horizontal load-displacement curve which under the different vertical load, we can get the yield load from these curve. Fig.9 is the yield point on the load surface, after connect all the yield point, we can get the bearing capacity yield envelope curve of pile under the combined load, from the figure we can see that under the combined load bearing capacity of pile yield envelope curve roughly elliptical in shape. This phenomenon is smillar with Meyerhof's empirical formula, however, in this test the ellipse center of yield envelope curve is not in coordinate origin.

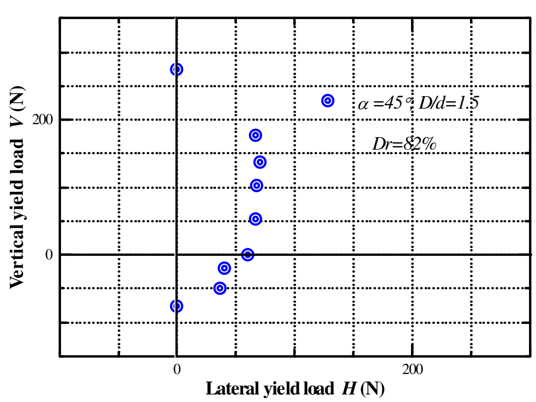


Fig.9 The yield points under H and V

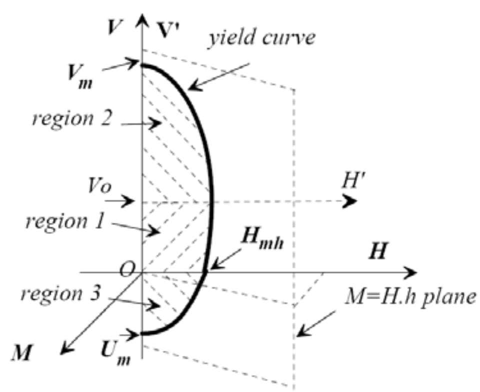


Fig.10 The coordinates of yield curve on M=Hh plane under H and V

According to test results shown in Fig.10, can be assumed that the yield envelope curve of pile's bearing capacity under the vertical, horizontal load is expressed as fellow

$$\left[\frac{V_1}{A}\right]^2 + \left[\frac{H_1}{B}\right]^2 = 1 \qquad (1)$$

Where V_1-vertical yield load , H_1-horizontal yield load，A, B respectively, the ellipse major axis and short axis, its value can be obtained from pile test results or the calculation, let H_1-V_1 coordinate system parallel translate V_0, thus, get H-V coordinate system, the relationship between the two coordinates can be expressed as fellows,

$$H_1 = H \text{ ; } V_1 = V - V_0 \qquad (2)$$

let equation (2) into equation (1) .

$$\left[\frac{V-V_0}{A}\right]^2 + \left[\frac{H}{B}\right]^2 = 1 \qquad (3)$$

According to boundary conditions $[V_m,0]$，$[-U_m,0]$ and $[0,H_{mh}]$，from equation (3) we can get V_0, A and B, its values are as follows,

$$V_0 = \frac{V_m - U_m}{2}, \quad A = \frac{V_m + U_m}{2}, \quad B = \frac{H_{mh}(V_m + U_m)}{2\sqrt{V_m U_m}} \qquad (4)$$

Where H_{mh} -ultimate horizontal bearing capacity of belled pile, the hight of load-point is h , V_m - ultimate pulling resistance of belled pile, U_m - ultimate push down bearing capacity of belled pile.

Let equation (4) into equation (3), then get equation (5), so the projection of the elliptical envelope curve on M=Hh space plane with test date to M=0 plane can be expressed as fellows,

$$\left[2\left(\frac{V}{V_m}\right) - (1 - C_1)\right]^2 + \frac{4C_1}{(C'_2)^2}\left(\frac{H}{V_m}\right)^2 = (1 + C_1)^2 \qquad (5)$$

where $C_1 = U_m / V_m$，$C_2' = H_{mh} / V_m$.

The scope of bearing capacity yield envelope shown in Fig.10 can be divided into three regions, the actal load in the region of 1, when the horizontal component force of yield load is a little bigger than ultimate horizontal bearing capacity H_{mh}, so the horizontal bearing capacity obtained from traditional design methods is in the safe side, however, when the actal load is in the region of 2 and 3, the horizontal component force of yield load is smaller than ultimate horizontal bearing capacity H_{mh}, so the horizontal bearing capacity obtained from traditional design methods is in the dangerous side. we also find from the Fig.10, in the aspect of vertical bearing capacity, that all the vertical component force of yield load is smaller than one-direction vertical bearing capacity V_m (U_m), that is to say, all the vertical bearing capacity obtained from traditional design methods is in the dangerous side, it is show that it’s necessary to consider the interaction of different kind of load in the process of pile foundation design

Yield envelope curve under the effects of moment load and horizontal load

We can get belled pile's load-displacement curves, using horizontal load test which on the effect of different highth of loading point, the curves as shown in Fig.11 and Fig.12, with the increase of highth of loading point, belled pile's horizontal bearing capacity are gradually reduced, pile head horizontal displacement $\delta = 10$ mm as the base of ultimate horizontal bearing capacity, we can determine the horizontal yield load H and yield moment M（M=Hh）， then get the yield point of bearing capacity in M-H coordinate plane which on the effect of moment load and horizontal load.

Let the yield point which is determined from the above method paint in Fig.12, connect all the yield point, then get the yield envelope curve which on the effect of moment load and horizontal load, its shape was oval-shaped. Assuming its envelope curve is approximated as ellipse， elliptical envelope curve can be expressed as fellows,

$$\left[\frac{H}{H_m}\right]^2 + \left[\frac{M}{M_m}\right]^2 = 1 \qquad (6)$$

where H_m- one- direction ultimate horizontal bearing capacity, M_m- one- direction ultimate moment bearing capacity, its value can be obtained from one- direction pile test or horizontal load pile test which is on two different height of load point.

Fig.12 show the comparison results between the test value of yield point and the envelope curve obtained equation (6), from the Fig.12, we can see that the yield envelope curve on the effect of combined load M and H can be expressed by ellipse which one- direction load H_m and M_m is its long, short axis. As the role of combined load reducing the ability of horizontal bearing capacity and bending resistance of pile, this also indicates the importance of taking into account the interaction of different load in the progress of pile foundation design.

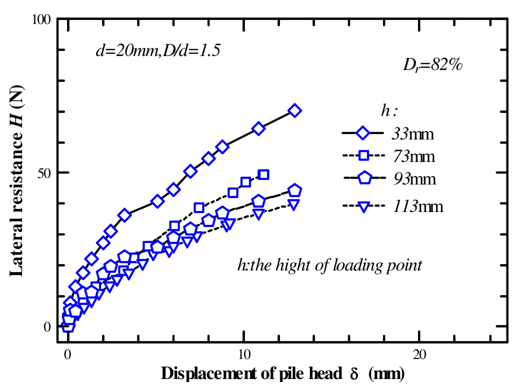


Fig.11 The H ~ δ courve under different heights of loading point

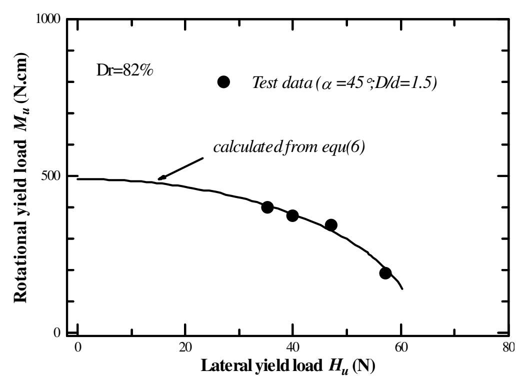


Fig.12 The comparison between test yeild points and calculated values

Three dimensional yield envelope surface of bearing capacity

In recent years, many scholars(Butterfield et al.1994, Gottardi et al.1993, Georgiadis et al.1988, Zhang et al.2000, Taiebat et al. 2000,2002, Gourvenec et al. 2003) did lots of study on bearing capacity mechanism of shallow foundation on the effect of combined load, Butterfield and Gottard(1994) put forward empirical formula on three dimensional yield envelope surface of bearing capacity of shallow foundations. But so far there is no report on three dimensional yield envelope surface of bearing capacity of pile foundation, to express characteristics of three dimensional yield envelope surface of bearing capacity of pile foundation under combined load, define a three-dimensional load space which is composed by vertical load, horizontal load and moment load, in this space it is easier to understand that defined ultimate bearing capacity of pile foundation as yield envelope surface, Fig.13 is the concept figure of three dimensional yield envelope surface, when the subject only under the vertical load and horizontal load, its bearing capacity characteristics(the relationships among V, U and H)can be represented by a notch on three dimensional yield envelope surface which is cut by surface of M=0 (Horizontal loading height h=0). In pile foundation design, if we can determine the three dimensional yield envelope surface of bearing capacity, it will be easily to check the security of bearing capacity of pile foundation under the combimed load, therefore, it is have important practical significance to study the characteristics of three dimensional yield envelope surface of bearing capacity of pile foundation.

Based on the above analysis results, for any plane V(it's a constant), assuming the shape of notch of three dimensional yield envelope surface can be express as fellows ,

$$\left[\frac{H}{H_m^{'}}\right]^2+\left[\frac{M}{M_m^{'}}\right]^2=1 \qquad (7)$$

$H_m{}'$ and $M_m{}'$ change with vertical load V, we can get the empirical formula on three dimensional yield envelope surface of bearing capacity of pile foundation from eqution (5) , (7) and continuity of hree dimensional yield envelope surface.

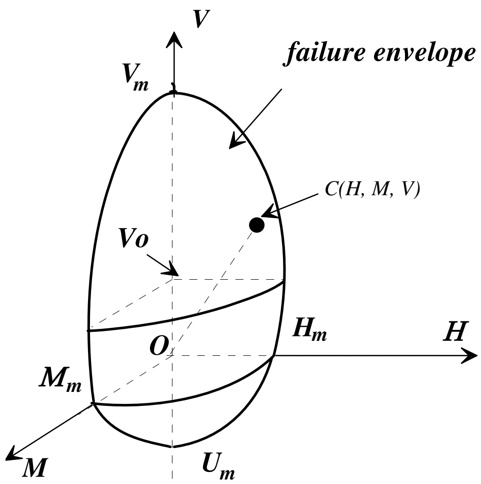
$$\left(\frac{V}{V_m}\right)^2-\frac{V}{V_m}\left(1-\frac{U_m}{V_m}\right)=\frac{U_m}{V_m}\left\{1-\left(\frac{H}{H_m}\right)^2-\left(\frac{M}{M_m}\right)^2\right\} \qquad (8)$$

To facilitate the comparison of test results, we eqution (8) non-dimension, let r=V /V_m, n=H /V_m, m=M /V_m into eqution (8),

$$r^2-r(1-C_1)=C_1\left\{1-(\frac{n}{C_2})^2-(\frac{m}{C_3})^2\right\} \qquad (9)$$

where $C_1=U_m/V_m$, $C_2=H_m/Vm$, $C_3=M_m/(d.V_m)$, d is the pile diameter.

From the above analysis we can see that three dimensional yield envelope surface of bearing capacity of pile foundation under effects of combined load is ellipsoidal, if we know or assume one- direction bearing capacity of pile foundation U_m, V_m, H_m and M_m, three dimensional yield envelope surface of bearing capacity of pile foundation under effects of combined load can be approximately obtained from equation (8) or (9), it will be a very practical and convenient way to use the envelope surface to check security of bearing capacity of pile foundation, the calculated values obtained from eqution (8) have good consistency with test values, the results shown in Fig.14.



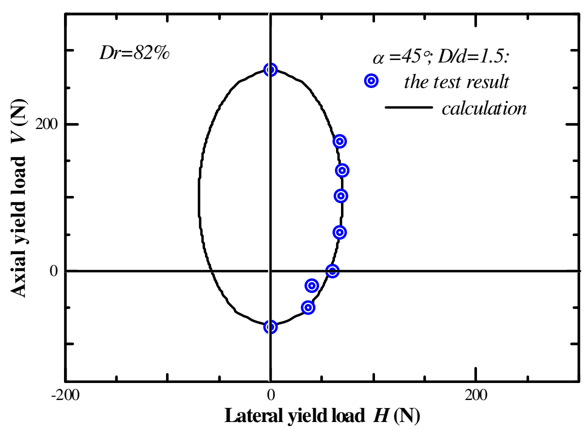


Fig.13 Yield envelope pattern **Fig.14 The comparison between test yield points and calculated value by equation (8)**

CONCLUSIONS

Through the model test of belled pile under vertical load, horizontal load and combination load, discuss the characteristic of bearing mechanism and yield envelope surface on belled pile, we can get some preliminary conclusions as follows.

The size of the vertical load has a certain effect on horizontal ultimate bearing capacity of belled pile, and there is a critical vertical load. when the constant vertical load is smaller than critical vertical load, with the increase of constant vertical load, horizontal bearing capacity of pile increase too, when the constant vertical load is larger than critical vertical load, with the increase of constant vertical load, horizontal bearing capacity of pile reduce.

When horizontal loads subject to the pile supporting the vertical load, the pile axial force re-distribution.

yield envelope curve of bearing capacity of pile under vertical load, horizontal load can be approximately expressed by ellipse, we can use ultimate bearing capacity U_m, V_m, H_m into eqution (5) to simulate the envelope curve.

Yield envelope curve under moment load, horizontal load can be approximately expressed by ellipse too, we can determine the envelope curve by eqution (6) base on horizontal load pile test results at two different hight of load point.

According to pile test results or theoretical calculations, if we can get one-direction ultimate bearing capacity U_m, V_m, H_m and M_m, three dimensional yield envelope surface of bearing capacity of pile can be get from eqution (8) or (9), from the view of design, it is a simple and practical method to use three dimensional yield envelope surface to check the security of pile foundation under the combined load

In the process of design and calculation of pile foundation,it must consider the interaction between Vertical load, horizontal load and moment load

ACKNOWLEDGMENTS

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Engineering Character of a New-Style Pretensioned Spun Concrete Nodular Pile

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ABSTRACT: As one of the primary pile style in soft soil, the pretensioned spun concrete piles are applied widely in many fields, such as building engineering, traffic engineering, port engineering, hydraulic engineering, etc. However, there are many limitations in technology, such as its lower shaft resistance, lower resistance to bending and shearing, poor linking manner and durability of connection between pile sections, etc. A new-style pretensioned spun concrete nodular pile is introduced in this paper. The main construction technology, mechanical bonding manner and bearing character are improved aiming on the shortcoming of the traditional pretensioned spun concrete pile. Through the compressive and tensile static loading test, the bearing capacity of the new-style pretensioned spun concrete nodular pile has much higher than that of the ordinary one by 26% at least. Especially, its ultimate uplift resistance can be increased enormously, which is the engineer quite concerned about. Finally, the bearing mechanism and how the new nodular pile improve the skin friction are developed. So the new-style pretensioned spun concrete nodular piles have many merits comparing to the traditional one, which is helpful to its spread and application in soft soil.

INTRODUCTION

In recent years, the pretensioned spun concrete piles are widely applied on building engineering, bridge engineering, hydraulic engineering and harbor engineering, etc. With both building height and weight increasing, the demand of developing the bearing capacity and construction technique is urgent. The pipe pile technology was born in

Japan, and nowadays is still well-known. Since 1980s, the technology have been developed rapidly in China. The production volume reached 0.3 billion meters in 2009, and increased by the rate of 10% to 15%.

The traditional prestressed concrete piles have many merits, such as the short construction period, good construction quality and no pollution by slurry, and so on. When the prestressed concrete piles are used in soft soil, there exist some defects. As the soil with the worse engineering character exists around the pile, the friction resistance induced between pile and soil is lower. The convenient connecting between piles adopt the manner of welding, which often affect the material strength and its durability under the adverse environment. In addition, the ordinary pipe pile has the lower tensile strength. Due to earthquake and wind loads, the overturning moment may induce the tension force in pile foundation. At the same time, tension loads on pile foundation can also increase when groundwater table rises. From these backgrounds, it is necessary to develop new types of pile foundations to overcompensate the above shortcomings.

The nodular pipe pile was first invented by Japanese. Since the early 1980s, the study of the nodular cylinder pile on construction technology and capacity mechanism had begun (Shoda, et al. 2007). Ogura, et al. (1987, 1988) investigated a nodular pile with some nodes in the body, performed the laboratory and full-scale tests and showed higher bearing capacity than the conventional cylinder pile. It had been also shown that the bearing mechanism is explained by the resistance for the lower side of nodes and the shearing between nodes. The comparison loading tests on the bearing capacity of cylindrical and nodular piles under the vertical and horizontal loading were conducted (Kanai 1988). The results of both tests implied that the nodular pile had more favourable bearing capacity. The bearing mechanism of nodular pile (multiple stepped pile) was aimed by model tests (Uchida et al. 2005; Shoda, et al. 2007). And it can be concluded that the nodular pile shows higher bearing capacity because of the load transmitted from the convex parts to the outside diagonally.

There were several researches on cast-in-place concrete piles with one- or two-bell shaped enlargements to increase both bearing capacity and tensile resistance. Watanabe et al. (2011) reported the investigation of construction methods of nodular cast-in-place concrete pile and nodular diaphragm wall. As a result of load tests, the nodular cast-in-place concrete pile and nodular diaphragm wall had large tension and compression resistance. The tension resistance at the nodular part and under-reamed part showed a large value. Sudo et al. (2008), Hirai et al. (2008) and Suzuki et al. (2011) reported cast-in-place concrete nodular piles supported a high-rise building, and described full-scale pile load tests. The test results indicated that the uplift tension resistance of nodular pile embedded within stiff deposit is larger than that of ordinary cylinder pile. Recently, the bearing capacity and load transfer mechanism of a static drill rooted nodular pile in soft soil areas were investigated (Zhou 2013). A group of experiments were conducted to provide a comparison between this new pile and the bored pile, and a 3D models were