Numerical Analysis of Belled Shaft Foundation in Thick Pusan Clays
대심도 부산점토에 적용된 종저말뚝(Belled Shaft foundation)의 수치해석 연구

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SYNOPSIS : The Pusan clays are soft and thick deposits and in some places, they reach even up to 50-70m. So, the pile foundations are inevitable in almost all cases. But they are significantly expansive when the length of the pile reaches about 70m. In this study, a comprehensive parametric study has been carried out in order to reduce the pile length and number of piles required in turn the cost of the foundation for particular building. A belled shaft pile has been optimizedfor a typical soil profile using the PLAXIS (FEM code). These results have shown a new direction of the pile foundation in Pusan, Korea. The results including the variation of contact pressures at the bottom of the bell, optimization of the angle of the bell and height of the bell in terms of the diameter of the shaft. And also, the design curves have been generated so that they can be directly used for design of belled shaft foundations. However, the structural strength criterion is being checked in the concerned laboratory.

Key words : Belled shaft pile foundation, Soft thick deposits, Optimization, Bell angle, Design curves, Contact pressure, PLAXIS code.

1. INTRODUCTION

Pile foundations are being widely used across the world. When the bearing soil at shallow depths is not competent enough to carry the super structural loads and also when the upper layers consist of soft clay, it is required to adopt more length of piles to meet the hard stratum. If column loads are considerably high, it is very essential to extend the pile tip location into the hard bearing stratum (gravel or rock), which usually meets at a depth of about 60-70m in Pusan clay deposits along the Nakdong River Estuary. For example, Fig. 1 shows a typical soil profile from one of the sites along the Nakdong River Estuary. It is well known that a point bearing belled shaft is designed to spread the design load in a point bearing over a large area to keep the unit bearing pressure on bearing soil within allowable limits and for economy by transferring the loads by means of relatively shorter shafts. The shaft with bell may be designed to transmit a portion of its load in skin friction and the remainder being transferred in point bearing alone. The height of the bell is normally disregarded for skin friction capacity. The bell can be constructed in shape of dome or it can be angled. For angled bells, the available underreaming tools can make angles of a 30 and 45 degrees with the vertical (Braja M. Das, 1999 & Hasi-Yang Fang, 1990).

In this study, an attempt has been made in order to reduce the pile length and number of piles by replacing the straight shaft with belled shafts. As a result, it has been found that enlarging the base of the pile, which is generally called as belled shaft foundation, is an appropriate solution to overcome the problem of pile length and number piles without compromising its performance with desired factor of safety. But, practically, making the bell shape at the bottom of the borehole is quite cumbersome due its stability problem during excavation and also there is a practical limitation of availability of underreaming tools. So, there is an emerging need to optimize the shape of the bell so that the loads will be dissipated over a large area, which can be made with the commercially available underreaming tools.

2. PARAMETRIC STUDY AND SOIL PARAMETERS

In order to optimize the shape of the bell, a parametric study has been carried out considering the following practical limitations: (a) most of the commercially available underreaming tools can cut bells with diameters as large as 3 times the diameter of the shaft and the possible angles are 30 and 45 degrees (Braja M. Das, 1999), (b) the height of the base of the bell (h_1) is about 0.15 to 0.3m (Braja M. Das, 1999). Fig. 2 shows a cross sectional view and different notations of the belled shaft. Parametric study involves 3 different heights (H) and different angles (α) for each height as shown in Table 1.

Table 1. Variation of dimensions of the bell.

Height of bell (H)	Angle(°), α								
1.0	30	32	34	36	40	44	45	52	60
1.5	30	32	34	36	40	44	45	52	60
2.0	30	32	34	36	40	44	45	52	60

The mean values of soil parameters for each layer, which are required input parameters for numerical modeling of belled shaft foundation using PLAXIS programme, have been taken from concerned tests and presented in Table 2.

Table 2. Soil parameters used in the modeling.

Soil layer	Su (kPa)	γ_t (KN/m^3)	R_{inter}	ϕ	K_x & K_y $\times 10^{-4}$ m/d	E_{ref} (kPa)	ν
Soft layer-1	17.47	16.5	0.5	0.01	8.64	535	0.3
Soft layer-2	39.15	17	0.5	0.01	8.64	1025	0.3
Soft layer-3	60.82	17	0.5	0.01	8.64	1516	0.3
Soft layer-4	82.50	17.3	0.5	0.01	8.64	2006	0.3
Soft layer-5	65.64	17	0.5	0.01	8.64	2496	0.3
Stiff layer	200	21.5	0.5	0.1	8.64	50000	0.2

3. MODELLING AND EXECUTION

A model of an axisymmetry with 16 nodes has been considered. Sufficient horizontal and vertical distances have been taken from the central axis and below the base of the bell respectively so that the total zone is much larger than the actual zone of influence can be covered. The zone of influence is considered based on the possible extent of pressure bulb in either direction below the bottom of the bell.

The sequence of load application is as follows: (a) Excavation after placing the casing, (b) Filling with concrete, (c) removing the casing, and (d) loading as shown in Fig. 3.

The stress-settlement response of the foundation soil has been obtained by incremental load application for all the cases considered in this study. For each case, allowable bearing capacity (q_a)has been taken depending on the following conditions:

(a) $q_a = q_u / 3$, if settlement, $s \leq 25mm$ at q_a.
(b) $q_a = q_u$ at s = 25mm, if s> 25mm at q_a.
where s is settlement and q_u is the ultimate bearing capacity.
But, in all the cases, case (b) was satisfied.

4. RESULTS AND DISCUSSION

The results of stress strain response and developed contact pressures for different cases have been obtained. In order to understand the effect of angle and height of the bell on allowable bearing capacity and distribution of the contact pressure, some results are discussed as follows: Figure 4 shows the stress-strain response (bearing capacity) where it is very clear that for a particular height of the bell, allowable bearing capacity slightly increases as angle (diameter) of the bell increases. Irrespective of the angle of the bell, the stress-strain response in the elastic range is the same for all the cases. In order to understand the effect of the height of the bell on the stress-strain response (bearing capacity), for a particular angle, stress-settlement response for different heights has been checked and plotted in Figure 5. It can be noticed that as the height of the bell increases, the bearing capacity also slightly increases as shown in Figure 5. It must be noted that both height and angle play a vital role in stress-settlement response of the foundation. However, as the bearing capacity is independent of width of the footing for cohesive soils, there is no significant increase in allowable bearing capacity with increase of diameter of the bell (angle and height).

But, the allowable bearing capacity increases relatively more with increase of height of the bell than that for angle of the bell. It may be due to marginal increase in skin friction on account of increase in resultant of vertical components over inclined surface of the bell, which is significant for higher heights of the bell.

The contact pressure (q) has been normalized with allowable bearing capacity (q_a) and presented in figures 6 and 7 in order to study the effect of both angle and height of the bell on the distribution of the contact pressure respectively. It can be noticed that the contact pressure is significantly decreasing with increase in angle of the bell. It can also be noticed that for a particular angle, contact pressure decreases with increase of height (diameter) of the bell. It can be seen that the contact pressure at the edge of the bell also decreases with increase in diameter (angle or height of the bell).

5. OPTIMIZATION OF THE BELL

In order to optimize the bell shape (angle and height of the bell), the mean contact pressure (q_m) and contact pressure at the center of the bell base (q_c) are plotted against both the angle and the height. Figure 8 shows that at smaller angles, the mean contact pressure decreases linearly with increase in height (diameter) of the bell. But as the angle increases, the trend of contact pressure variation changes from linear to non-linear.. As the angle of the bell increases, the role of height in dissipating the stress decreases. At greater angles, the height greater than 1.5m does not have any significant role in dissipating the stresses.

The contact pressure at the center of the bell has been plotted and presented in Figure 9. It can be seen that for any angle, the q_c decreases rapidly with increasing height of the bell up to certain level, beyond which the pressure across the bell becomes uniform for all the bell angles. It turns out that to avoid overstressing in the belled shaft, it is desirable to adopt a specified height depending on the shaft diameter. *It is noted that the minimum height of the bell is about 1.67 time diameter of the shaft (d=1.5m), which is true for different angles of the bell.*

The contact pressure at the center of the bell (q_c) has also been plotted against angle of the bell for different heights of the bell and presented in Figure 10. It is also very clear that qc decreases almost linearly with increase in angle of the bell for every height of the bell. But, with a special observation, it can also be noted that the rate of decrease of q_c decreases with increasing height of the bell as shown in Figure 10, when height starts to take care of desired role.

Even though the contact pressures at the base of the bell (both q_c and q_m) are significantly decreasing with the increase of angle of the bell, the maximum angle of 45^o can only be provided due its practical limitations such as availability of underreaming tools.

As a result, it can be understood that both angle and height of the bell no need to be maximum. But, depending on the practical limitation, extend the possible parameter (height or angle) so that the desirable diameter of the bell can be obtained.

6. CONCLUSIONS

Numerical analysis has been carried out for modeling the belled shaft on Pusan clays. As a result, the following conclusions have been drawn for the particular soil profile:

(1) The contact pressure decreases with increase in diameter of the bell (i.e. angle of the bell and height of bell). But commercially available underreaming tools can make maximum angle of 45^o. So provide the maximum angle by considering the appropriate height of the bell such that $D \leq 3d$.

(2) The height of the bell equivalent to 1.67 times the diameter of the shaft would ensure minimum contact pressure distribution. Further increase in height of the bell, does not play any significant role in reducing the contact pressure.

(3) As the bearing capacity is not width dependent for cohesive soils, there is no significant increase in allowable bearing capacity. However, a little increase took place, which may be due to a marginal increase in skin friction on account of resultant of vertical components over the vertical surface of the bell.

(4) As the applied load is distributing over a large area of the bell, pile length and number of piles can be greatly reduced for a particular project.

(5) Some of the basic relations have been generated and they have been used for approximate optimization and design of the belled shaft for a known mean contact pressure.

(6) As the results are limited to a soil profile, it is strongly recommended to get the same results for couple of sites to reinforce the conclusions from this study.

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Hsai-Yang Fang 1990. Foundation Engineering Handbook. VAN Nostrand publications.

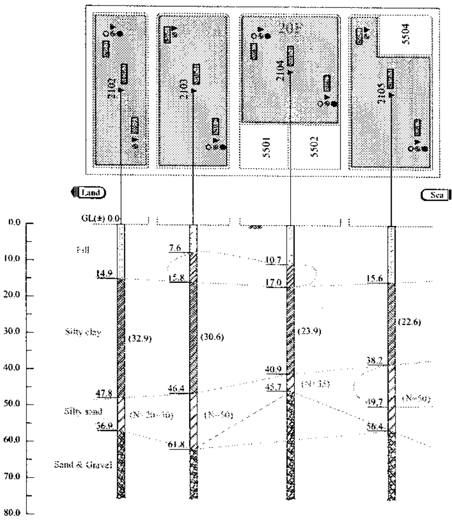


Figure 1. Soil profiles at the Shinho site

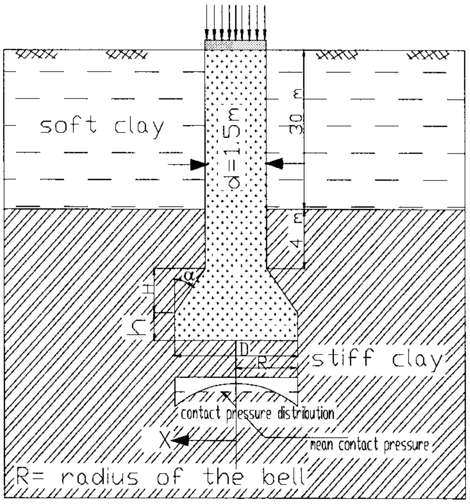
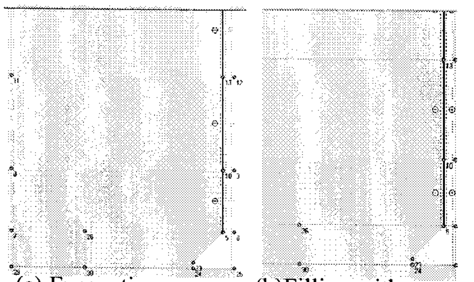
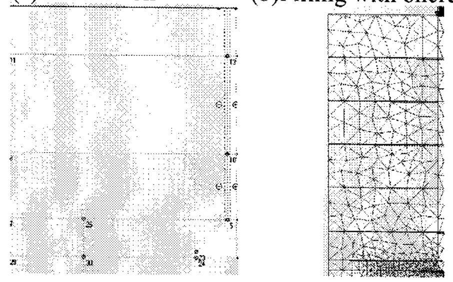


Figure 2. Cross sectional view of belled shaft



(a) Excavation (b)Filling with oncrete



(c) Removing the casing (d) Loading

Figure 3. The sequence of the load application

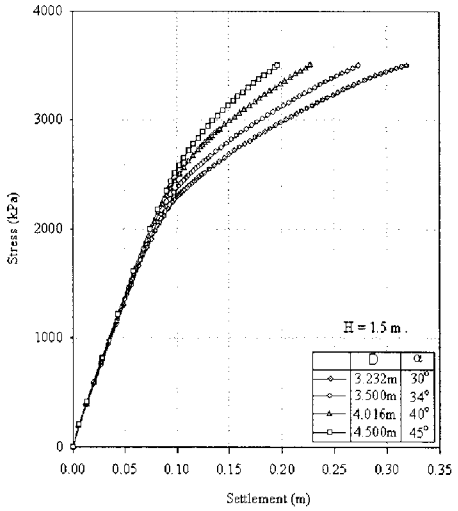


Figure 4. Effect of angle of the bell on Stress-settlement response.

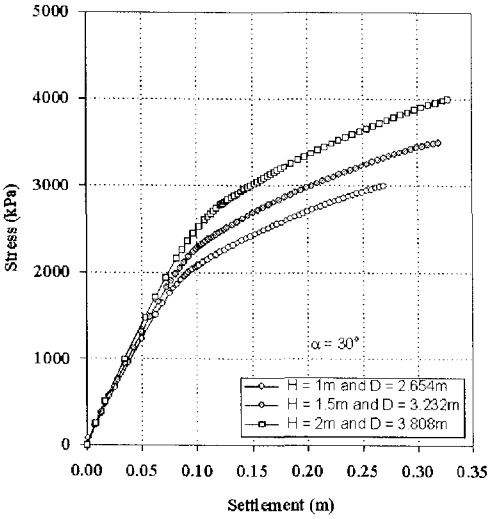


Figure 5. Effect of height of the bell on stress-settlement response

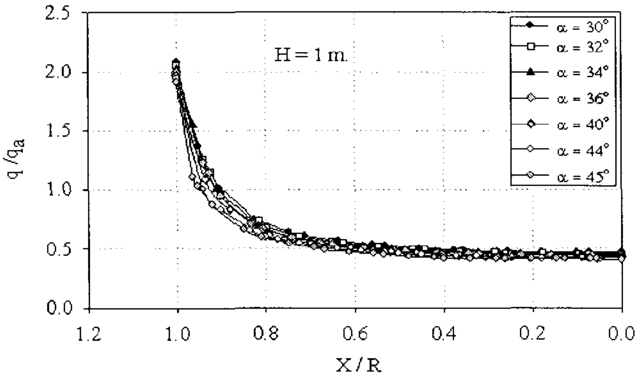
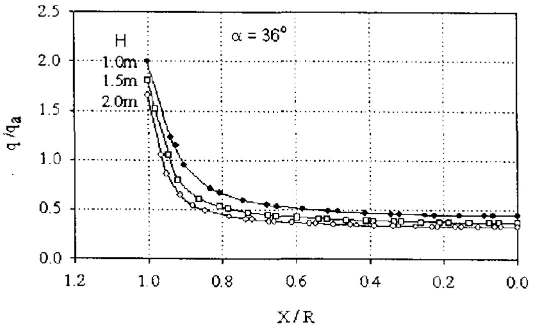


Figure 6. Effect of angle on contact pressure distribution



. Figure 7. Effect of height or diameter of the bell on distribution of contact pressure

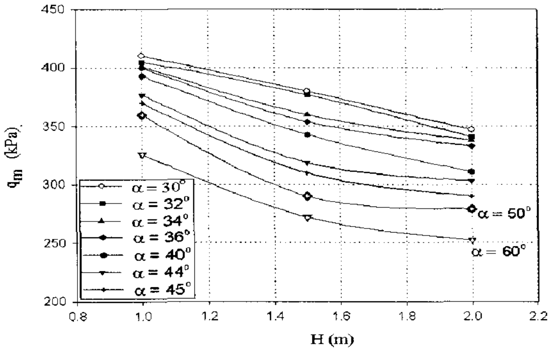


Figure 8. The variation of mean contact pressure with height and angle of the bell.

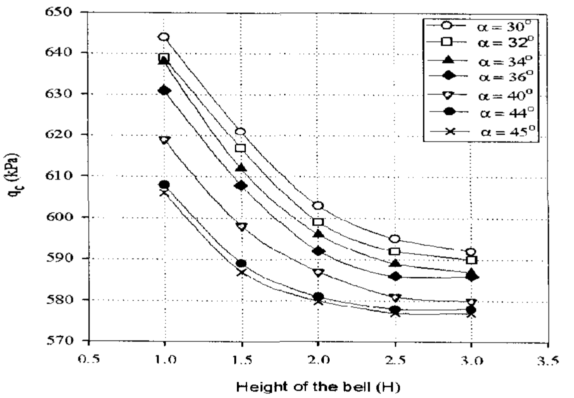


Fig. 9 The variation qc with angle and height of the bell.

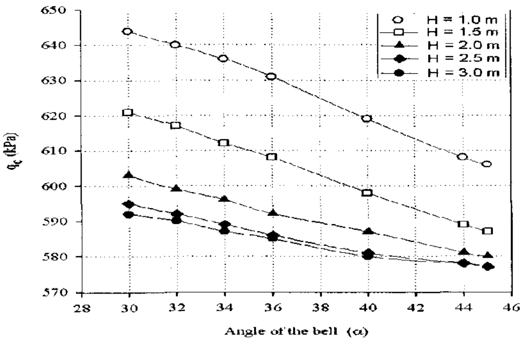


Fig. 10 The variation of the qc with angle of the bell at different heights of the bell.