A calculating model of cap-pile-soil interaction

Un modèle de calculation de longrine-pieu-sol

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SYNOPSIS It was found in model tests by authors that there are "Weakening", "Barrier" and "Strengthening" effects acting on a cap-pile-soil system. This was also proved afterward by large scale in-situ tests of pile groups in a district near the Yellow River. The importance of settlement to the cap-pile-soil interaction is emphasized. A calculating model is proposed for estimating the bearing capacity and settlement of pile foundations.

INTRODUCTION

The importance of cap-pile-soil interaction has attracted foundation engineers' attention for quite some time, but in pile foundation design "block failure" concept still dominates in practice. The aim of this paper is to search for a calculating model reflecting the behavour of interaction and applicable to engineering practice.

It is learned that the cap-pile-soil interaction which is caused by the relative displacement among cap, pile and soil includes the following main aspects: (1) The pile cap induces a "weakening effect" which restricts the mobilization of the side resistance in upper sections of piles. (2) The pile group induces a "barrier effect" which constrains the soil inside the piles to be squeezed out sideward. (3) In soils with internal friction the stress induced by the cap increases the soil bearing capacity at pile tip and also increases the normal stress and frictional resistance between piles and soil. It is called "strengthening effect". Under different geological conditions, the role of each of these effects is different.

The development of pile-soil relative displacement is characterized by:
(1) To a certain depth the displacement between pile and soil is limited by the pile cap pressure. Therefore the load transfer from pile sides to soil around is developing from tip to top.
(2) The study of interaction usually has more practical meaning for short friction pile groups in which the elastic compression of pile is insignificant.
(3) Pile-soil relative displacement occurs only when piles are placed apart far enough (e.g.>3d) or the soil is rather soft.
(4) Under certain loading, the pile-soil relative displacement ΔS below depth z may already reaches or exceeds the $(\Delta S)_{fmax}$ which is the displacement required for mobilizing ultimate side resistance of piles. Therefore the amount of load transferd by pile shaft is limited. Below z, the side resistance becomes constant or gradually decreases (in soils of strain softening) (see Fig. 1).
(5) The average amount of relative displacement in the whole pile length lies between two values, the pile top settlement S_G and zero. The former shows the soil inside piles does not settle. The latter indicates the piles and soil act as a unit. The case happened in reality lies in between these two.

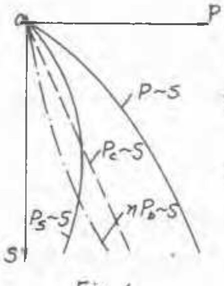

Fig. 1

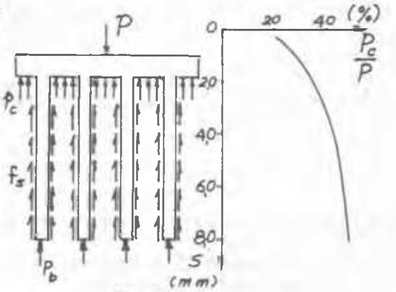

Fig. 2

BASIC STARTING POINTS FOR ESTABLISHING A CALCULATING MODEL

(1) The allocation of load is (Fig. 2)

$$P=P_c+nP_b+n\pi d \sum_{i=1}^{n} l_i f_{si} \qquad (1)$$

where P_c-total pressure on the cap bottom, $P_c=A_c p_c$; A_c-effective area of cap (pile section deducted); p_c-stress on the cap bottom; P_b-end resistance of pile; n-number of piles; l_i-length of the i section of pile; f_{si}-side resistance on i section; d-pile diameter.
(2) The stress-strain characteristics in pile itself and in pile-soil boundary are very compilcated spatial problem. Attention is only paid here to the approximate stress state in the points on the pile-soil boundary in order to be able to take more factors into account and makes the calculation simple.
(3) Based upon the following physical phenomena, an approximate method of load transfer analysis is proposed.
a. The mobilization of side resistance accords with load transfer theory. The relation between (ΔS) and f_s can be expressed as:

$$f_s = F_1 (\Delta S) \quad (2)$$

b. The final settlement of soil between piles should satisfy both the deformation induced by the cap and the mobilization of certain amount of side resistance.

c. For rigid pile, the settlement at any depth S_{pz} are equal to that of pile top S_G. For compressible pile, the compression δ_{sz} of pile section above depth z should be considered.

d. Since the displacement of any section of piles in a pile group ($S_{pz}-\delta_{sz}$) and the settlement of soil between piles (S_z) both are known, then the pile-soil relative displacement equals $(\Delta S)_z = (S_{pz}-\delta_{sz}) - S_z$, $(\Delta S)_z$ may be used to derive the side resistance f_s at point z (see Fig. 3).

e. With known subsurface condition, the relation between the settlement of pile tip $S_{pb}-\delta_{sb}$ (δ_{sb}-compression of whole pile length) and P_b can be expressed by a known function which will be discussed later.

f. Pile foundation settlement will induces stresses on the boundary between piles and soil correspondingly. The resultant of vertical components of these stresses should balance the loading on pile foundation.

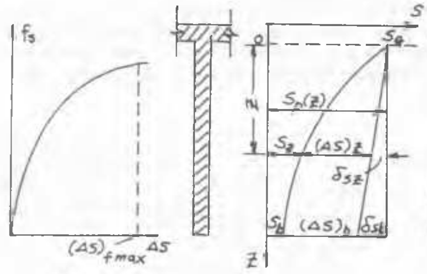

Fig. 3

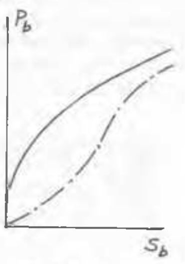

Fig. 4

FUNDAMENTAL FORMULA FOR LOAD TRANSFER ANALYSIS

(1) The formula for the allocation of load E_q. (1) can be rewritten as:

$$P = nP_b + p_c + n\pi d l \bar{f}_s \quad (3)$$

(2) All terms of E_q. (3) are functions of the settlement of pile top S_G, as following:

a. Considering the influences of installation of pile, soil conditions and the geometry of piles, the relation between the end resistance P_b and the settlement of pile tip S_b can be expressed by a cubic equation. (Fig. 4)

$$P_b = a_0 + a_1 S_b + a_2 S_b^2 + a_3 S_b^3 \quad (4)$$

where a_0, a_1, a_2, a_3-coefficients derived from the result of loading test of piles installed by same method. They can also be determined by deep seated loading plate or pressuremeter test. For rigid pile, $S_b = S_G$, for compressible pile, $S_b = S_G - \delta_{sb}$. (Fig. 4).

Considering the strengthening effect acting on the end resistance by the pile cap pressure, concept of stress dispersion may be introduced to evaluate the increment of overburden pressure at pile tip $\Delta\delta_x$ which increases P_b to P_b^1, thereby, $P_b^1 = KP_b$. K-coefficient of strengthening (K > 1.0). In general case, K value in sand is a linear function of the overburden pressure, then:

$$P_b^1 = KP_b = \left(\frac{\gamma l + \Delta\delta_z}{\gamma l}\right) P_b \quad (5)$$

where γ-effective unit weight of soil. If the ground consists of c-ϕ soil, P_b can be increased by the q value in the q N_q term in the bearing capacity formula of deep foundation. If the soil at pile tip is soft, Terzaghi formula should be used. In case of friction pile installed in homogeneous soil, the calculation method based on the mechanism of expansion of cavities in infinite soil mass may then be used.

b. From model tests it is learnt that due to the barrier effect, p_c~S_G shows linear relation. i.e.

$$p_c = CS_G \text{ and } P_c = A_c C S_G \quad (6)$$

same notations used as Eq. (1). Coefficient C can be determined as follows: for cohesive soil, use the tangent slope of the P-S curve of plate load test; for cohesionless soil, use Terzaghi-Peck emperical formula derived from the result of plate load test with size effect considered. As for layered foundation, C can be calculated by layerwise summation method.

c. The relation between ΔS and $\bar{f}_s$ may be as follows: for certain conditions of soil and pile material, the required $(\Delta S)_{fmax}$ is comparatively constant and small (< 10mm for sand and < 4mm for clay). When $(\Delta S) < (\Delta S)_{fmax}$, the load transfer function of f_s~(ΔS) can be expressed as:

$$f_{sz} = F_1 (\Delta S)_z \quad (7)$$

then the total side resistance P_s is given by

$$P_s = \pi d \sum_{i=1}^{n} \int_0^l (f_{sz})_i \, dz = \pi d \sum_{i=1}^{n} \int_0^l F_1 (\Delta S)_{zi} \, dz \quad (8)$$

Where $(\Delta S)_{zi}$-the pile-soil relative displacement of any points in the pile length of i pile. If $(\Delta S)_{zi}$ equals to the difference between pile top settlement S_G and the soil settlement S_z obtained by Boussinesq's equation (or even minus the compression of the pile δ_{sz}), then integrate $F_1(\Delta S)_{zi}$ over l to find P_s.

In considering the strengthening effect of the pile cap pressure on the end resistance f_s, Boussinesq's theory also can be used to calculate the horizontal stress increment in soil.

$$(\Delta\delta_x)z = (K_x)z \cdot p_c \quad (9)$$

where K_x-coefficient of horizontal additional stress. By integrating Boussinesq's formula, the increment of f_s induced by $\Delta\delta_x$ is written as:

$$\Delta f_{sz} = (\Delta\delta_x)z \; F_1 \; (\Delta S)_z / tg\delta \quad (10)$$

where δ-the friction angle between soil and pile, then integrate it over l and remained procedures as those above mentioned.

The basic formulas proposed only point out some comprehensive calculating principles. Detailed investigation for a concrete method of calculation is out of the scope of this paper.

CONCLUSIONS

It may be concluded that the theory of load transfer is applicable to analysing the bearing capacity and settlement of pile foundations with cap-pile-soil interaction under consideration. With such a model, portions of load carried by the cap, the pile shaft and the pile tip can be evaluated and also the P-S curve of a pile foundation can be predicted.