

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Pile Foundations in Soft Soils

Fondations sur Pieux dans les Sols Tendres

Y.X. TONG Principal Geotechnical Engineer, Eastern China Power Design Institute, Shanghai
 Q.H. CHEN Lecturer, Tongji University, Shanghai
 X.L. CHEN Engineer, Nanjing Hydraulic Research Institute, Nanjing, People's Republic of China

SYNOPSIS This paper reports on experience of pile foundations and design concepts in Shanghai and its vicinity including: (1) Empirical rules for estimating pile bearing values based on static cone penetration resistance; (2) Case history of an instrumented heavy pile foundation with field observations of pore water pressure, soil displacement, etc.; (3) Long-term performance records of pile-supported structures; and (4) a tentative design method which may affect a saving of some 20% or more of the piles in a group by allowing larger settlements.

INTRODUCTION

Methods for predicting pile bearing capacity, behavior of pile foundations during construction and afterwards, and new design concepts, as presented in this paper, represent outcome of many years' experience and study in Shanghai and its vicinity. It is hoped that these will be of general interest to foundation engineers dealing with soft soils.

PILE BEARING CAPACITY FROM CPT

Based on static load tests on 42 precast R.C. piles 18-45m long in Shanghai and Eastern China coastal regions, empirical formulae have been established for estimating skin friction (f_s) and point bearing (R_p) values from cone penetration resistance (q_c) with satisfactory results, typical geological profiles and cone dimensions being given in Fig.1.

For normally consolidated or lightly overconsolidated soils of soft to medium consistency, at a depth not less than 6-8m below ground level, and for overconsolidated soils of medium to stiff consistency not less than 20m below ground level,

$$f_s = 1/20 q_c \quad (\text{for } q_c \leq 1000 \text{ kN/m}^2),$$

$$f_s = 25 + 1/40 q_c \quad (\text{for } 1000 < q_c < 3000 \text{ kN/m}^2)$$

$$f_s = 100 \text{ kN/m}^2 \quad (\text{for } q_c \geq 3000 \text{ kN/m}^2):$$

For low-cohesion silts and very fine sand,

$$f_s = 1/50 q_c \quad (\text{for } q_c < 5000 \text{ kN/m}^2),$$

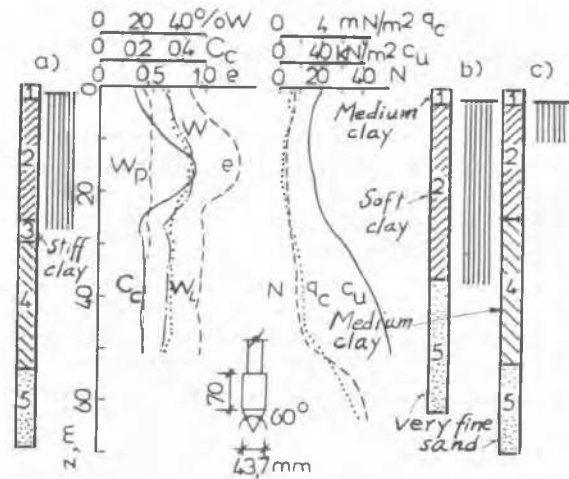


Fig.1 Typical Geological Profiles and Cone Dimensions

$$f_s = 100 \text{ kN/m}^2 \quad (\text{for } q_c \geq 5000 \text{ kN/m}^2);$$

For soft to medium, cohesive or cohesionless soils at a depth not exceeding 6-8m below ground level, irrespective of q_c -value,

$$f_s = 20 - 25 \text{ kN/m}^2.$$

Point bearing value R_p is taken equal to q_{cb} ,

$$q_{cb} = \frac{q_{cb1} + q_{cb2}}{2}$$

where q_{cb1} and q_{cb2} are, respectively, the

average q_c -value within the depth range d_1 above pile end and within the range d_2 below pile end. For piles ending in sand or stiff clay, $d_1=8D$ and $d_2=4D$, where D is the side or diameter of the pile; and for piles ending in cohesive soils of soft to medium consistency, $d_1=4D$ and $d_2=D$. In the former case, q_{cb} will be computed with the following formula if there is weak layer within the depth range d_2 ,

$$q_{cb} = \frac{q_{cb1} + \frac{q_{cb2} + q_{cb2(\min)}}{2}}{2}$$

Where $q_{cb2(\min)}$ is the minimum q_c -value within the depth range d_2 . Accuracy of the pile bearing capacity as rated from the above empirical formulae, compared with static load test values, is given in Table I.

TABLE I

Accuracy of Empirical Formulae of Pile Bearing Capacity

Deviation	No. of Piles	Percentage
< 5%	16	38%
5 - 10%	15	35.8%
10 - 15%	4	9.5%
15 - 20%	2	4.8%
> 20%	5	11.9%
Total	42	100%

CASE HISTORY OF AN INSTRUMENTED FOUNDATION

The heavy silos foundation mat (35.2m x 69.4m) on 604 R.C. piles 30.7m long at 1.90m centers was well instrumented and monitored since its construction in May 1974. Driving piles into the soft soil led to high hydrostatic excess pressure having a maximum value equal to 1.4 times the overburden, the extent of the effected zone increasing considerably with time. The excess pressure dissipated rather quickly and the degree of consolidation amounted to 70-80% near the end of construction, Fig.2. Serious soil deformations, with maximum values of both vertical and horizontal displacements up to 40-50cm were observed. Heaving of the soil mass is estimated to be some 40% of the total volume of the piles driven into the soil suggesting that the soil had been compacted somewhat during pile driving. It was found that the deeper soil layers had been more heavily compacted and that the deep layers even at a distance 20m away from the pile group had been subjected to displacement of significant magnitude. Pile driving caused previously

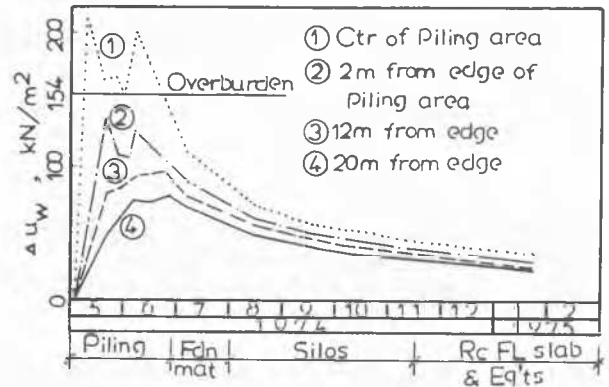


Fig.2 Hydrostatic Excess Pressure

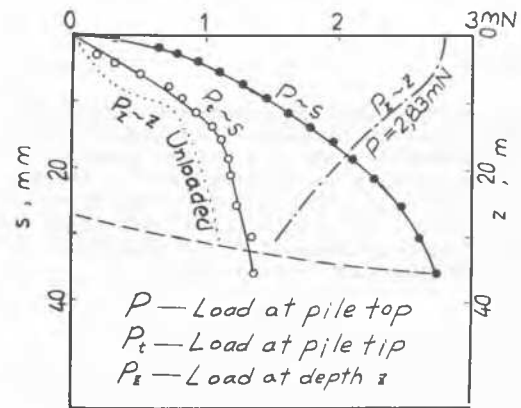


Fig.3 Loading Test

driven piles to heave as much as 12cm and to displace horizontally as much as 5cm; subsequent loading test yielded adequate bearing value with tolerable settlement, the residual values of point bearing and average negative skin friction after unloading being 1100kN and 20kN/m² respectively, Fig.3, thus no re-driving was required. Live load 220kN/m² was imposed on the silos in Oct. 1975, and the settlement of the silos reached 6.5cm in 1980, Fig.4, curve c, the total foundation pressure then being 390kN/m². The surrounding ground surface settled 6cm more than the silos, Fig. 4, curve d. Negative friction load decreased from 600kN to 250kN, maintaining a value about 400kN up to now, Fig.5. Contact pressure between the R.C. mat and the foundation soil decreased from 30kN/m² to zero in three years' time, showing that the load finally became supported by piles only.

LONG-TERM PERFORMANCE RECORDS

Following is a brief resume of some of the performance records of pile-supported structures in Shanghai. It is seen that a pile foundation will be expected to tilt much less than a shallow foundation having an equal value of total settlement, as shown in Fig.6. Structures supported by piles not less than 25m in length and ending in a hard layer (Fig.1b) usually settle 5-10cm, bringing no harm to the superstructures, Fig.4. curve a,b,c. But where soft soils underlie the hard stratum supporting the pile end (Fig.1a), or in the case of friction piles (less than 20m in length), Fig.1c, the settlement usually amounts to 20-40cm and sometimes even to 70cm (Fig.7). Cracks may develop in R.C. frames, when $s \approx 30\text{cm}$ and $\Delta s/l > 0.004$ (Yu et al, 1965), Fig.8, curve a, Δs being the differential settlement over a length of l . Friction pile foundations with $B/L < 2$ (B =width of foundation, L =length of piles), $L=7-15\text{m}$ and net foundation pressure $p_n=80-120\text{kN/m}^2$, usually settle 10-20cm, and cause no structural damages.

A TENTATIVE DESIGN METHOD

The following design method aims at saving the

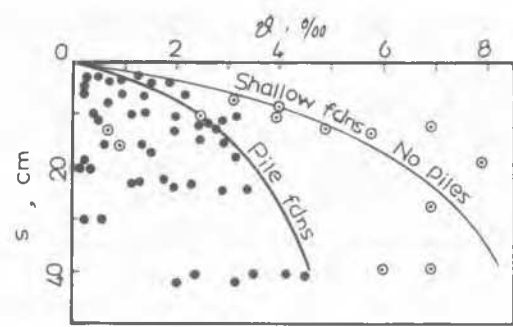


Fig.6 Relation between Tilt & Settlement

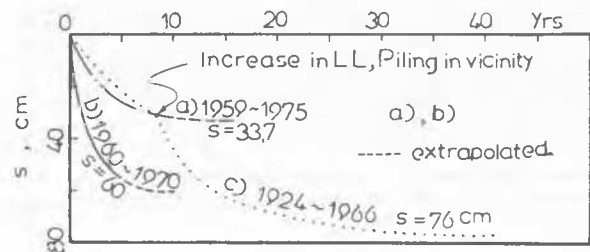


Fig.7 Settlement Records

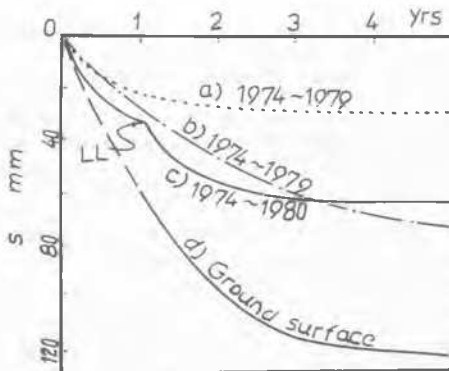


Fig.4 Settlement Records

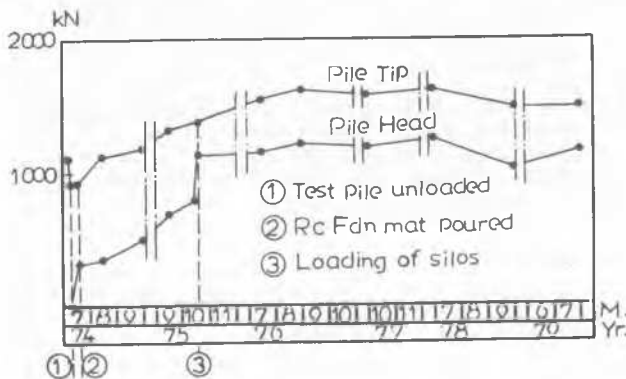


Fig.5 Negative Skin Friction

number of piles in the group. The basic requirement is that the total load Q must be smaller than the ultimate bearing capacity of the pile foundation as a whole with respect to base failure.

When Q is smaller than (or equal to) the ultimate bearing capacity of a single pile (p_u) multiplied by the number of piles (n) in the foundation, Q will be, in the long run, supported by the piles alone. In such cases, settlement of the pile foundation may be taken equal to that of an equivalent mat located at an "equivalent friction length" L_e above pile end. This may be conceived on the ground that as the highly compressible soil amidst the piles consolidates, skin friction on the upper portion of the pile shaft is gradually released and transferred downwards; such have been reported by large-scale model group pile tests in Shanghai soils (Tong, S.X., 1979) and elsewhere (Tong, Y.X., 1979). Thus, it is assumed as a working hypothesis that it is the fully developed skin friction on the lower part L_e together with the end bearing if any that supports the load Q on the pile group. So we have

$$Q = n \cdot p_u = n \cdot R_p \cdot F + n \cdot f_{Le} \cdot U \cdot L_e$$

where F is the projected area of pile end, U is the circumference of the pile section and f_{Le} is the average skin friction on L_e . When $Q < n \cdot R_p \cdot F$, Q will be carried by end bearing only, with $L_e=0$; this corresponds to Shanghai

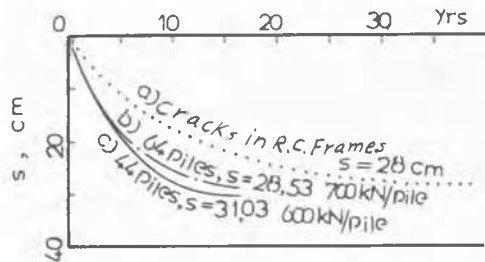


Fig. 8 Settlement Records

experience reported earlier (Yu et al, 1965); further increase of number of piles will not be beneficial, Fig. 8, curve b and c. For friction piles ($R_p=0$), with allowable skin friction (f_a) equal to $1/3 f_{Le}$, then $L_e=1/3 L$; this happens to be in agreement with Terzaghi's rule (Terzaghi and Peck, 1948, 1967). For the case of Fig. 7, curve b, where $f_a=1/2 f_{Le}$ and so $L_e=1/2 L$; the extrapolated final settlement $s=60\text{cm}$ is greater than $s=34.5\text{cm}$ (calculated for $L_e=0$) and $s=42.6\text{cm}$ (calculated for $L_e=1/3 L$).

When Q exceeds n times the single-pile capacity, i.e.

$$Q > n \cdot p_u = n \cdot R_p \cdot F + n \cdot f_L \cdot U \cdot L \quad ,$$

the soil will always remain in contact with the foundation mat carrying the difference $(Q - np_u)$, skin friction on piles and end resistance (if any) being fully mobilized so that $L_e=L$. The number of piles may be further reduced to such an extent that the foundation soil carry the greater part of Q , resulting in what has been called "settlement reducers" (Burland, Broms, and De Mello, 1977). In the thirties the design of short friction pile foundations in Shanghai usually assumed that the foundation soil carry 60kN/m^2 and the rest of Q be supported by pile friction at 10kN/m^2 , about half of its ultimate value 20kN/m^2 . Thus, assuming that the net pressure $p_n=100\text{kN/m}^2$, the rule in fact required the piles to carry $2(100-60)=80\text{kN/m}^2$ with the soils carrying the remaining 20kN/m^2 . Many pile-supported structures so designed have performed properly provided that $B/L < 2$.

CONCLUSIONS

Predicting pile bearing capacity with static cone penetration test can be used to advantage. Instrumented observations on closely spaced pile group revealed the development of considerable hydrostatic excess pressure, large soil displacements and significant residual stresses in soils, showing that pile group behavior is quite different from that of single

pile. The concept for designing pile foundations outlined in this paper has led to new interpretations of Terzaghi's rule and early Shanghai practice. Alternative designs of pile foundations with different L_e/L values have

pointed out that the proposed method may lead to a saving of some 20% of the piles in a group, nearly equal to that expected by Bishop (Bishop, 1971). This cuts down the cost of pile foundations at the expense of allowing larger yet tolerable settlements. The conceptions are rudimentary but it is believed that such simple rather than sophisticated approach should be useful to practising engineers in pile foundation design.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. Chen Zhuchang and many others for their helpful suggestions during the research work, and wish to thank particularly Professor Yu Tiaomei for his encouragement and advice throughout the preparation of this paper.

REFERENCES

- Bishop, A.W. (1971). Conference Conclusions Related to the Future, Behaviour of Piles, 218, Inst. of C.E., London.
- Burland, J.B., Broms, B.B. & De Mello, V.F.B. (1977). Behaviour of Foundations and Structures, Proc. 9th Int. Conf. Soil Mech. Found. Engg. (2), 495-546, Tokyo.
- Terzaghi, K. & Peck, R.B. (1948, 1967). Soil Mechanics in Engineering practice, 479 1st ed.), 549-550 (2nd ed.).
- Tong, S.X. (1979). Research on the bearing capacity and deformation of model pile groups in soft soils, Presented to 3rd National Conf. on Soil Mech. Found. Engg., Hangzhou (in Chinese).
- Tong, Y.X. (1979). Structural strength and bearing capacity of long piles in soft soils, Symposium on soft soils, Nanjing (in Chinese).
- Yu, T.M., Shu, W.Y. & Tong, Y.X. (1965). Settlement analysis of pile foundations in Shanghai, Proc. 6th Int. Conf. Soil Mech. Found. Engg., (2), 356-359, Montreal.