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Settlement Analysis of Pile Foundations in Shanghai

Analyse du tassement des fondations sur pieux à Shanghai

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SUMMARY

Settlement records are reported for 14 buildings and structures on pile foundations in Shanghai, with computed settlements within an accuracy of 30 to 50 per cent; tentative suggestions are given for limiting values of settlement and differential settlement of reinforced concrete frames on pile foundations, which are somewhat higher than those for shallow foundations.

SOMMAIRE

Cet article présente une série de quatorze cas de tassements d'édifices et de structures construits sur pieux à Shanghai. Les tassements calculés diffèrent de 30 à 50 pour cent avec les tassements observés. Des suggestions sont présentées pour limiter les valeurs du tassement absolu et des tassements différentiels des charpentes de béton armé construites sur fondation de pieux, qui sont plus élevés que les tassements des fondations peu profondes.

SHANGHAI SOIL consists of quaternary alluvial deposits of the lower Yangtze Valley. The water table is very close to the surface of the ground; for considerable depth the soil consists mainly of a highly compressible cohesive soil, except that there may be a desiccated surface crust and another relatively stiff clay layer at a depth of, say, 20 meters or more.

Experience with pile foundations in Shanghai has aroused international interest for many years (*Proc. ICOSOMEF*, 1936). Since liberation, there have been many developments in the field of foundation engineering. Short timber piles designed on nominal values of skin friction, commonly used for ordinary buildings, have given way to shallow foundations on the surface crust; it is now customary to design shallow foundations according to limit conditions of settlement (Chen and Shu, 1963). The use of pile foundations is now limited mainly to precast reinforced concrete and cast-in-place concrete piles, 20–30 meters long and bearing on the relatively stiff clay layer. These piles are superior to short piles with respect to bearing capacity and settlement.

This article reports the settlement records of 14 buildings and structures on pile foundations, together with their computed settlements (Table I). The period of observation is between 3 and 7 years, and settlement is in general approaching equilibrium. Typical examples of settlement records are given in Fig. 1.

As shown in Fig. 2, the pile foundation is assumed to act as a deep foundation ($a \times b \times L$), net pressure at the level of pile tip being equal to

$$p = (\Sigma P/A) - \gamma H = (\Sigma P/ab) - \gamma H, \quad (1)$$

where ΣP is the sum of the load of superstructure and weight of foundation and the soil mass $a \times b \times L$ including piles, taking into account the buoyancy of groundwater. Here the pressure distribution angle α along the length of the piles has not been considered, because preliminary computations taking $\alpha = 3^\circ - 6^\circ$ gave too small values of computed settlements; nor has the top of the compression zone been assumed to commence at two-thirds of the length of piles, as

suggested by Terzaghi and Peck (1948, p. 479), because the bearing layer at pile tip is in general relatively stiff, and the design load per pile does not exceed 40 to 60 tons.

Settlement of the pile foundation is computed by the following formulae:

$$s' = \sum_1^n \frac{p_i h_i}{E_i}, \quad E_i = \frac{1 + e_1}{a} = \frac{p_2 - p_1}{e_1 - e_2} (1 + e_1), \quad (2)$$

where p_i is the net increase in vertical pressure along the centre line of the pile foundation, in the layer h_i within the compression zone, according to Boussinesq's solution; and E_i is the compression modulus of the layer h_i . The bottom of the compression zone is assumed to be at the depth where net increase in pressure in the foundation soil is equal to 10 per cent of the overburden pressure. Compression moduli of the foundation soil are determined on $e-p$ curves from laboratory oedometer tests, taking $p_1 = \gamma Z$ and $p_2 = \gamma Z + p_z$ and corresponding values of e_1 and e_2 ; corrections for compression indices (Terzaghi and Peck, 1948, p. 61) have not been considered, because oedometer tests were in general run up only to 4 to 5 kg/sq.cm.

In order that computed final settlements may be compared with observed values, it is necessary to find the extrapolated final settlement from settlement curves. Among the available methods for extrapolation (Nichiporovich and Tsubulnik, 1961), the hyperbolic-curve method has been used:

$$S_t = S[t/(a + t)], \quad (3)$$

where values of S_t are observed settlements at time t , S is the extrapolated final settlement, and a is an empirical parameter. According to experience at Shanghai, the value S is usually quite reliable when the ratio of the last observed settlement S_t to S exceeds 0.75. For the majority of the data presented in Fig. 3, the ratio $S_t/S > 0.75$.

As shown in Fig. 3, accuracy of computed settlement in most cases lies within the following limits:

$$S = (1.5 \sim 0.7)S', \quad (4)$$

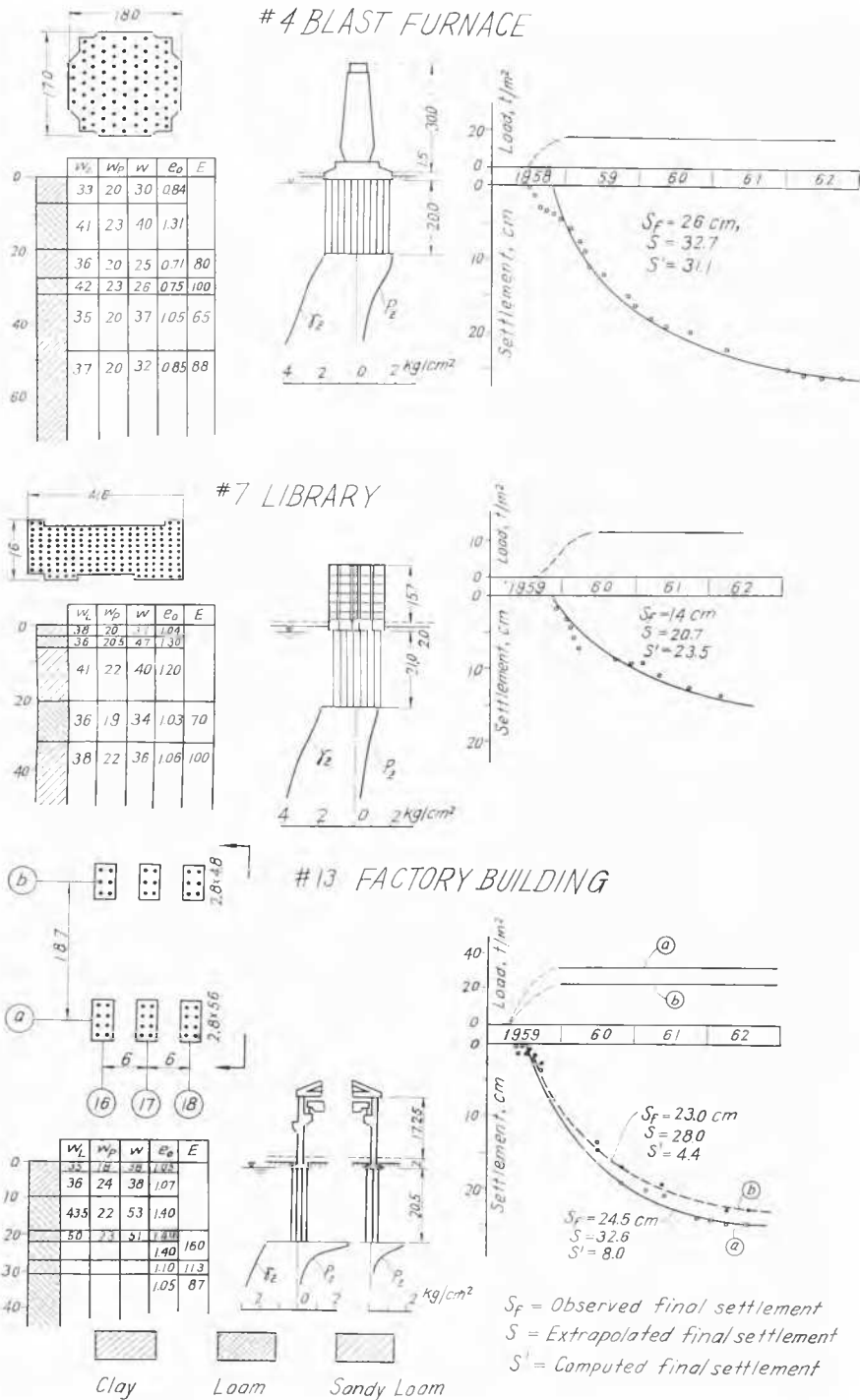


FIG. 1. Typical settlement records.

which is as accurate as computed settlements for shallow foundations.

Structures with simple plans and supported on a great number of evenly spaced piles are more suitable for settlement analysis. The load of structures should be carefully estimated according to actual conditions; for instance, the design capacity of the cold storage building (No. 9) is 20,000 tons, but settlement analysis is based on the average storage of 16,000 tons. Single footings of factory buildings

(Nos. 10-13) supported on few piles and subject to rather uncertain crane loads are more difficult to analyse; for example, the computed settlements of two factory buildings (Nos. 12, 13) are too small, probably because of the frequent operation of cranes, up to 1,000 times in 24 hours.

As shown in Fig. 3, computed settlements generally err somewhat on the smaller side; this deserves further investigation. Furthermore, settlement analysis of single pile, single footing on few piles, and pile foundation subject to repeated

TABLE I. SUMMARY OF SETTLEMENT RECORDS

No.	Description	Dimensions of foundation (m)		Embedded length of piles (m)	No. of piles		Period of settlement observation (years)	Observed final settlement S_f (cm.)	Extrapolated final settlement S (cm.)	Computed settlement S' (cm.)
		Over-all	Single footing		Total	Under single footing				
1	45-m chimney	Oct., $d = 10.4$		20	47		5.1	12	16.1	13.3
2	45-m chimney	$\phi 9$		20	53		6.4	18	21	16.3
3	98-m chimney	$\phi 20$		21	135		3.1	4.5	5.3	7.3
4	Blast furnace	Oct., $d = 17-18$		20	85		4.2	26	32.7	31.1
5	Coal tower	20.1×21.4		21	230		3.9	29	31.1	21.4
6	Coking furnace	16.4×81.7		22	692		3.4	36	38.3	28.3
7	Library, 6 storeys	16.1×41.6		21	167		2.3	14	20.6	23.4
8	Apartment, 8 storeys	Irr.		22	280		3.7	14	18.3	23.2
9	Cold storage, 7 storeys	48×60	$4.8 \times 4.8,$ @ 6 m. centres	25	676	8-9	3.4	20	32.3	29.1
10a	Single-storey factory buildings	3.6×2.6		21.5	5		5.7	—	6.3	10.0
10b		3.2×2.6		"	4		5.7	—	8.5	12.2
10c		"		"	4		5.7	—	10.5	12.2
10d		3.6×4.0		"	6		5.7	8.2	10.8	9.5
10e		3.2×4.0		"	6		5.7	—	9.0	8.0
11a	Single storey factory buildings	2.75×5.3		25	7		4.5	6.1	8.5	12.7
11b		3×6.3		"	7		4.5	8.0	13.7	11.6
12a	Single-storey factory buildings	3.7×6.2		22	6		2.8	20.2	28.6	7.25
12b		"		"	6		2.8	—	35.7	7.2
12c		5.2×7.2		"	12		2.8	20.5	27.8	10.2
12d		"		"	12		2.8	18.0	23.0	8.3
13a	Single-storey factory buildings	2.8×5.6		20.5	8		3.2	24.5	32.6	8.0
13b		2.8×4.8		"	4		3.2	23	28.0	4.4
14a	Power plant	ext. col.	2.5×4	23	6		4.5	15.7	22.8	15.0
14b		RC frame	5.2×11.8	"	36		4.5	27.7	45.8	40.1
14c		turbo-generator	6.9×12.5	"	45		4.5	29.3	30.3	24.4
14d		boiler	5.2×14.5	"	33-40		4.5	28.9	43.5	35.3

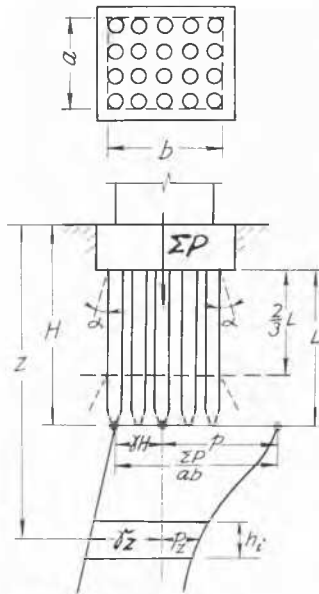


FIG. 2. Computation of final settlement.

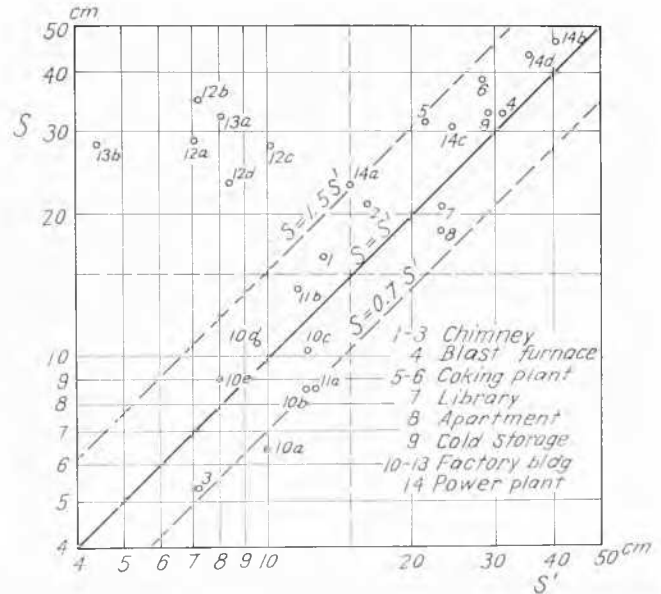


FIG. 3. Comparison of computed final settlement S' with observed values S (extrapolated).

loads and vibrations is of course much more complicated.

Data shown in Fig. 4 have been compiled from observations of settlement and structural damage of six reinforced concrete structures in Shanghai and a nearby city having similar geological conditions. It is tentatively suggested that

limiting values of settlement and differential settlement of reinforced concrete frames on piles are respectively 30 cm and $0.003L$, where L is the distance between adjacent columns; these values are somewhat higher than those accepted for shallow foundations according to Shanghai

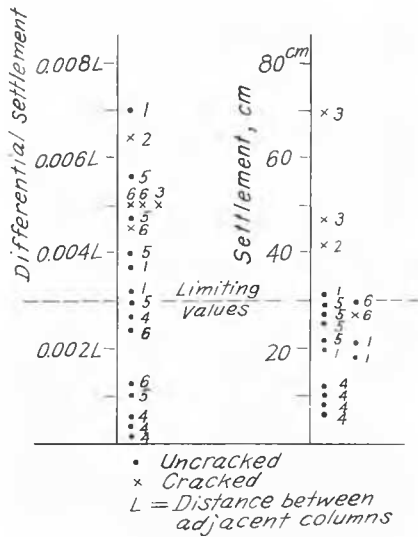


FIG. 4. Limiting values of settlement and differential settlement of reinforced concrete frames on pile foundations.

practice, namely, 20–30 cm and $0.002L$. From observations on a great number of other structures, it is tentatively suggested that pile foundations on soft soil probably settle more slowly than shallow foundations, so that creep of structural materials may adapt to foundation deformations.

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REFERENCES

- CHEN HWEI-KANG and SHU HWEI-LING (1963). Design of shallow foundations in Shanghai based upon limit condition of settlement. *Chinese Jour. Civil Engineering*, Vol. 9, No. 4 (in Chinese).
- NICHIPOROVICH, A. A., and T. I. TSIBULNIK (1961). *Forecasting settlement of hydraulic structures on cohesive soils*, pp. 64–82. (In Russian.)
- Proc. ICOSOMEF (1936). Papers C-4, F-12, I-3, I-14.
- TERZAGHI, K., and R. B. Peck (1948). *Soil mechanics in engineering practice*. Pp. 61, 479.