Countering Excessive Settlement of a Warehouse Founded on Piles

Mesures pour remédier au tassement excessif d'un entrepôt construit sur pieux

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SUMMARY

Settlement behaviour of a large six-storey structure founded on piles and having a flat slab construction for each floor was studied. The consolidation of the silty clay stratum underneath the pile tips with only the dead load of the structure, (hardly 50 per cent of the total design load) gave rise to excessive settlements and cracks developed in the lower floors. In order to partially relieve the extra stresses, preloading at the periphery was performed. Uniform settlement under the extra live load was also assured by excavating a stepped basement in the centre.

The paper deals with the analysis of the above problem and details the computations made to determine the effect of the fill at the periphery, and the size and depth of the basement required.

SOMMAIRE

On a étudié le comportement au tassement d'un édifice de six étages construit sur pieux dont les planchers étaient constitués de dalles en béton. La consolidation de la couche d'argile silteuse sous-jacente à la pointe des pieux, sous le poids propre de l'édifice, a produit des tassements excessifs et occasionné des fissures dans les planchers inférieurs. Le poids propre de l'édifice correspondait à la moitié des charges totales. Afin de réduire les contraintes excessives, on a appliqué une charge à la périphérie de l'édifice. On s'est aussi assuré d'un tassement uniforme sous l'action des charges vives en creusant une cave au centre de l'édifice.

On présente dans cet exposé l'analyse de ce problème et les calculs qui ont établi l'effet de la charge périphérique ainsi que les dimensions requises de la cave.

THE PRESENT STUDY describes the settlement behaviour of a six-storey structure, 545 ft by 182 ft in area, with a flat slab construction for each floor and column spacing of about 18 ft by 20 ft in the form of a grid. Each column was supported on 110-ton, cast-in-place Franki piles in groups of 2 to 4. The piles could not be driven very deep, reaching an average depth of only 42 ft. No proper soil exploration was carried out before the driving of piles. Load tests conducted by loading to 1½ times the design load on a single pile and a group of three piles gave satisfactory results.

About nine months after the superstructure was started, settlement was noticed. It increased with the addition of floors and after about a year and a half, when all six floors were up (barely 50 per cent of the total design load), the settlement in the centre exceeded 6 in. A proper soil exploration was then undertaken which revealed that the piles passed through a soft silty clay layer ($N = 7$) of 37 ft and rested in a 27-ft medium sand stratum ($\phi = 32°$, $N = 15$). Below this was another soft silty clay layer ($N = 7$) of 28 ft which was followed by a stiffer clay layer ($N = 20$), 30 ft thick. These layers were primarily responsible for the settlement. By this time cracking of the lower floors had begun and immediate remedial measures were necessary.

RELEVANT OBSERVATIONS

The settlement of the entire structure due to the dead load was saucer-shaped. The structure was under great stress because of the differential settlement between adjacent columns, especially in the lower floors. The upper floors were under less stress because the settlement appeared to have progressed gradually with the addition of the upper floors. In order that the building would be structurally safe when the full design load was applied, it appeared necessary to partially equalize the settlements so that the near yield point stresses in the lower floors of the structure would be relieved, without causing significant stresses in the upper floors. Measures were also needed to prevent further differential settlement when the additional load (live load) was put on.

The structure was divided into three sectors by providing expansion joints in the superstructure portion only. The average length of piles (42 ft) was also small compared with the large width (182 ft) of the building. The pressure bulbs resulting from the individual pile groups thus combined in effect at a higher strata and produced a state in which the piles could not play their important role of transferring the load deep enough to the proper strata. From the very nature of the settlement pattern, Fig. 1, it can be seen that the subsoil strata have been subjected to a loading similar to that under a flexible raft with a uniformly distributed load. A cross-section of the soil strata with their various levels along with the average depth of piles is given in Fig. 2. The average values of soil properties are given in Table I. Two static penetration curves using a 60° cone, 10 cm square, are given in Fig. 3.

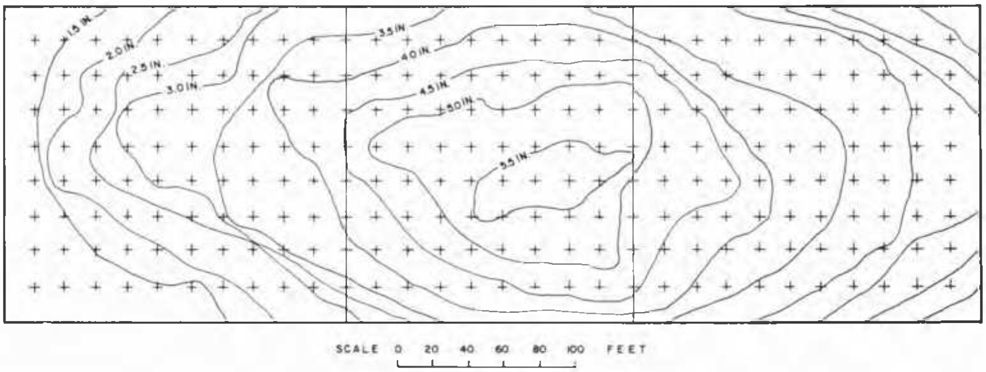

FIG. 1. Contours showing settlement of ground floor.

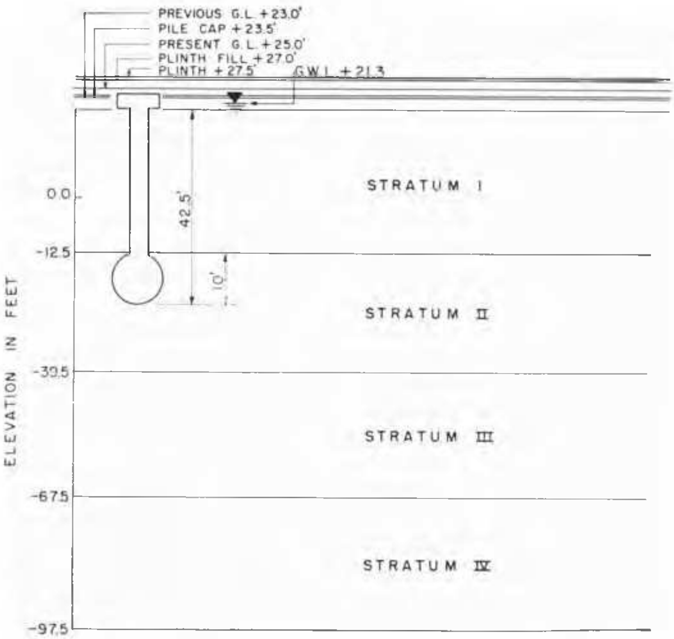

FIG. 2. Cross-section showing various soil strata.

TABLE I. SOIL DATA

Stratum	Liquid limit (per cent)	Plasticity index (per cent)	Dry density (lb/cu. ft.)	Natural water content (per cent)	N (blows/ft)
I	40	20	90	30	7
II	non-plastic		95	30	15
III	35	15	82	30	7
IV	60	40	95	25	20

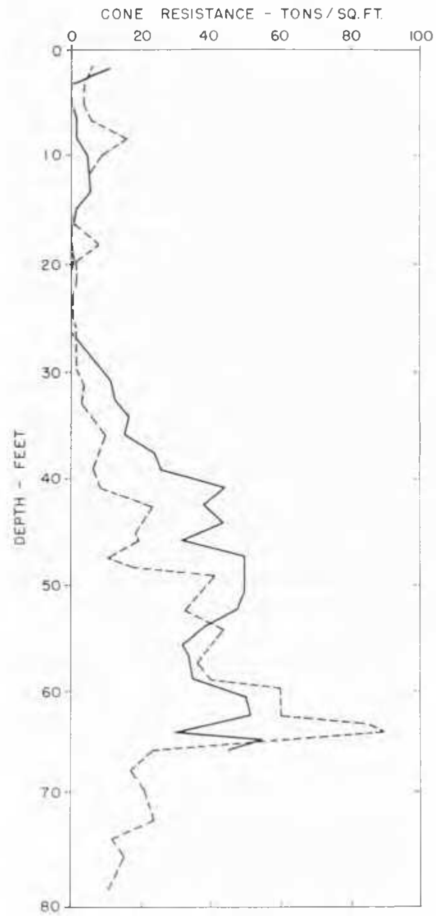

FIG. 3. Static cone penetration resistance curves.

SETTLEMENT FROM BUILDING LOAD

The average values of actual settlements of the ground floor under the dead loads of the building only were 5½ in. at the centre and 1½ in. at the corners. The values of expected settlements worked out theoretically under the above loading are 6.14 in. and 2.20 in. at the centre and corners respectively. (The theoretical calculations are given in Appendix A.)

It was therefore assumed that settlements under the building loads were almost complete and further progressive settlement, if any, could occur at the asymptotic stage of the time-settlement curve only.

SETTLEMENT UNDER THE TOTAL DESIGN LOAD

In calculating this, the plinth fill was taken as +27 ft indicating a 4 ft fill above the original ground level of +23. The estimated settlement was 10.57 in. at the centre and 4.68 in. at the corners. This meant a further settlement of 4.43 (10.57 − 6.14) in. at the centre and 2.48 (4.68 − 2.20) in. at the corners over and above the settlement due to the building load alone. The differential settlement for which precautionary measures were therefore adopted was only 1.95 in. (Details of the calculations are given in Appendix B.)

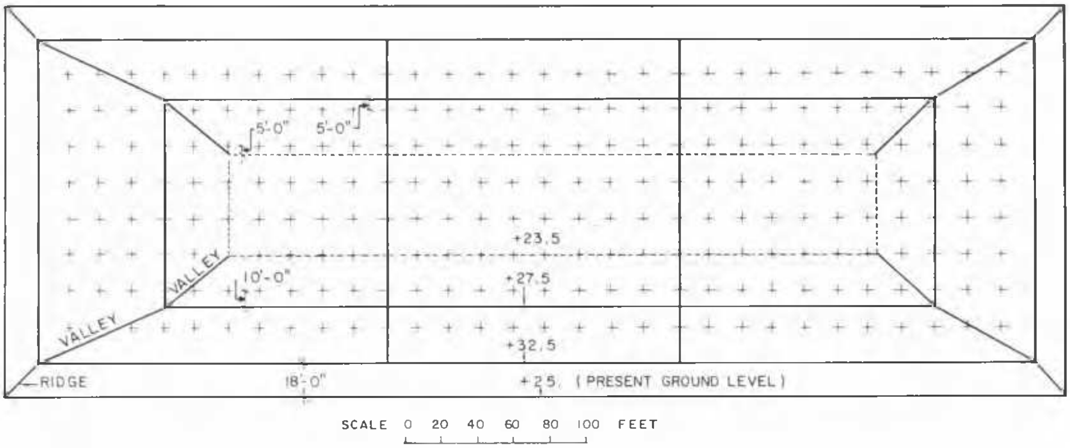

FIG. 4. Filling with soil for reducing differential settlements.

RELIEF OF STRESSES IN THE BUILDING

Immediate relief measures consisting of a 4-ft excavation at the centre, and preloading the outer edges, of the building were recommended (Fig. 4). The settlement of the outer bays contributed by the preloading was rather low. (The calculations are given in Appendix C.) The over-all relief measure suggested was the relief of the stresses in the floor slabs to some extent by reducing the differential settlement.

MEASURES TO COUNTER THE EXPECTED SETTLEMENT OF THE BUILDING DUE TO TOTAL DESIGN LOAD

The differential settlement between the centre and the corners could only be counteracted by relieving the soil overburden in the central part of the building. This could be effected by providing a basement, the level of which could be just below the existing pile caps (+20). Calculations of the estimated settlement with the excavation up to the proposed basement level were carried out (Appendix D). The settlement at the centre was estimated to be 8.14 in. Without the basement, the settlement as estimated in Appendix B was 10.57 in. Hence the reduction in settlement at the centre with the provision of the basement was of the order of 2.43 in. which was sufficient to counteract the expected differential settlement of 1.95 in.

It may be mentioned here that the calculations of the settlement have been made at the centre only without taking the boundary effect of the excavation into consideration. However, this boundary effect would have only a negligible effect on the ultimate settlement of the structure.

The recommended size of the basement is shown in Fig. 5. In recommending the size and depth, the settlement contours already recorded from the building loads were adopted as the guiding criteria.

Work on the basement which was to have a properly designed bottom concrete raft began simultaneously with the preloading at the periphery for the equalization of settlements. The additional load on the entire building (live load) could only be applied when both the equalization of settlements (as far as possible from considerations of the

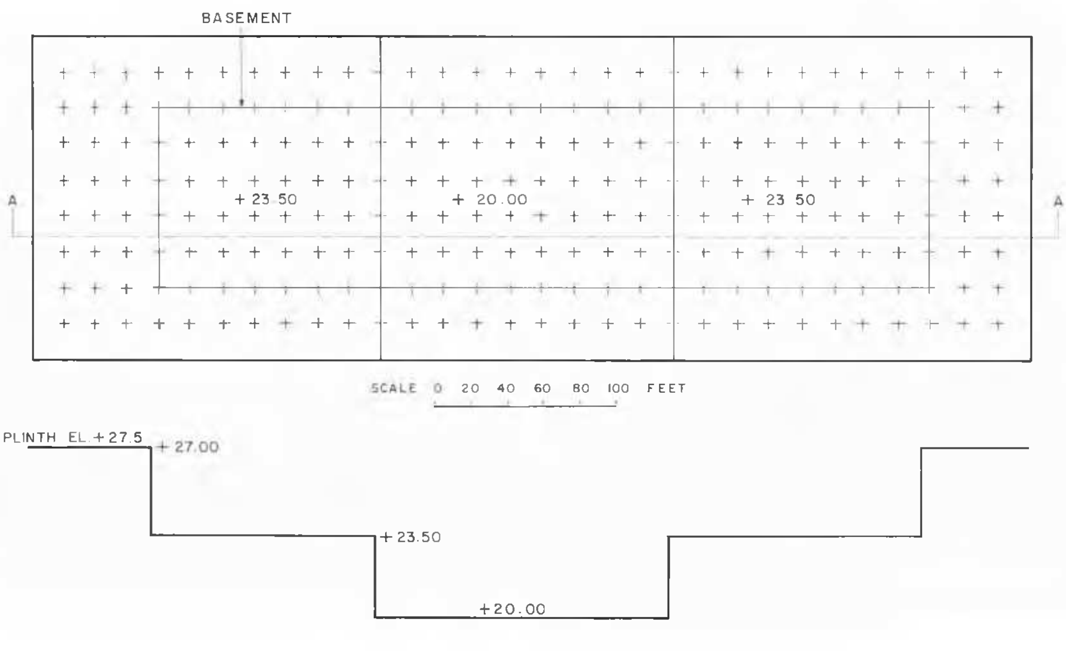

FIG. 5. Plan and section of basement.

structural safety of the slab) and the provision of the basement would be complete. Regular observation of the settlement at various points within the building is being continued and study of the data has revealed that the differential settlement of the edges with respect to the centre has been reduced by about ½ in.

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APPENDIX A

The entire building load distributed over its foundation area plus the added weight of the piles and the pile caps (buoyant weight below water table), and the weight of 2 ft of fill weigh 0.51 tons/sq.ft. The total loads due to the weight of the superstructure and the piles have been assumed to act at a level 8.5 (one-third the length of the pile from the bottom) uniformly. The settlements contributed by the various soil strata have been compiled as given below. The clay layer between level −8.5 and −12.5 in Stratum I is considered to contribute no significant settlement.

Settlement for Stratum II

Settlements have been worked out by considering the N values and the load acting on the stratum using the Peck, Hansen, and Thornburn (1953) curve relating the N value, the width of footing, and the allowable settlement of one inch.

From the above-mentioned relations, for $N = 15$ and for footing widths exceeding 20 ft, the settlement due to a load of 0.43 tons/sq.ft. is found to be 0.36 in. The load due to the 2 ft of fill (0.08 tons/sq.ft.) is 0.08 by .98 Newmark factor = .078 tons/sq.ft. and the corresponding settlement = 0.06 in. Hence the total settlement is 0.42 in.

Settlement for Stratum III

The settlements have been worked out by determining the average values of void ratios from e-log p curves for the stratum and by using the expression

$$S = \frac{e_1 - e_2}{1 + e_1} H$$

The self-weight of the soil strata up to the centre of stratum III is 1.06 tons/sq.ft. Increment pressure is 0.48 tons/sq.ft. at the centre and 0.12 tons/sq.ft. at the corner. The Newmark factor calculated and used for the above computations are: at the centre, (a) for 2 ft of fill, .836, (b) for weight of structure including piles, .960; at a corner, for 2 ft of fill, .242; for weight of structure, .252.

The values of void ratios for loads of 1.06 (p) and 1.06 + 0.48 ($p + \Delta p$) = 1.54 are 0.760 and 0.738 respectively, for which the settlement at the centre is 4.21 in. and for a corner 1.34 in.

Settlement for Stratum IV

$p = 1.35$ tons/sq.ft., $\Delta p = 0.429$ and 0.112 tons/sq.ft. for centre and corner respectively. Newmark factors at a depth of 74 ft at centre are (a) for fill, 0.736 and (b) for building load, 0.854. The corresponding figures for corner are 0.233 and 0.244. The settlement works out to be 1.51 in. for the centre and 0.44 in. for corner positions.

Total calculated settlements are given in Table II.

TABLE II

	At the centre (in.)	At the corners (in.)
Stratum II	0.42	0.42
Stratum III	4.21	1.34
Stratum IV	1.51	0.44
TOTAL	6.14	2.20

APPENDIX B

For the total design load on the foundation, taking into consideration the fill up to the proposed plinth level (+27), the settlements will be 0.81 (total design load) +0.05 (for piles) = 0.86 tons/sq.ft.

Stratum II

The load contributing to settlement = 0.86 tons/sq.ft. (due to building load only) +.98 Newmark factor by 0.16 tons/sq.ft. (due to 4 ft of fill) = 1.01 tons/sq.ft. Thus, settlement = 0.84 in., for $N = 15$.

Stratum III

$p = 1.06$ tons/sq.ft., $\Delta p = 0.960$ tons/sq.ft. for the centre position and = 0.254 tons/sq.ft. for the corners. The settlements will be 7.82 in. for the centre and 3.19 in. for corners.

Stratum IV

$p = 1.35$ tons/sq.ft., $\Delta p = 0.852$ tons/sq.ft. for the centre position and = 2.47 tons/sq.ft. for corners. The settlement will be 1.91 in. for the centre and 0.65 in. for corners.

Total calculated settlements are given in Table III.

TABLE III

	Centre (in.)	Corner (in.)
Stratum II	0.84	0.84
Stratum III	7.82	3.19
Stratum IV	1.91	0.65
TOTAL	10.57	4.68

APPENDIX C

The settlement due to surcharge at the corners has been worked out on the basis of an average height of 5.5 ft (above +25) of loading with soil over an area 40 ft by 40 ft.

Settlement of Stratum II

The load at the sand stratum due to the fill = .428 by 0.25 tons/sq.ft. = 0.11 tons/sq.ft. The settlement for the above = 0.09 in.

Settlement of Stratum III

$p = 1.06$ tons/sq.ft., $p + \Delta p = 1.14$ tons/sq.ft. Settlement = 0.57 in.

Settlement of Stratum IV

$p = 1.35$ tons/sq.ft., $p + \Delta p = 1.41$ tons/sq.ft. Settlement = 0.11 in.

Total settlement = 0.09 + 0.57 + 0.11 = 0.77 in.

The calculations are approximate, however, because changes in pressure intensities are low and values of void ratios cannot be read very accurately from the *e*-log *p* curves.

APPENDIX D

The estimates of reduced settlement due to the excavation have been based on calculation of the stress changes at the various levels of the strata when the excavated material was removed (Leonards, 1962), the level of excavation being taken as +20. As the original ground level was +23, the real excavation would be only 3 ft.

Stratum II

The stress at the centre of this stratum resulting from an equivalent load for excavation = 0.34 by .792 = .27 tons/sq.ft. The settlement due to this load (N = 15), 0.22 in., will be avoided by providing a basement. Hence the net settlement contributed by Stratum II = 0.84 in. (see Appendix B) − 0.22 in. = 0.62 inches.

Stratum III

The Newmark reduction factor for the centre of Stratum III with respect to level +20 and the area as given in Fig. 5 is 0.61. For Stratum IV, the factor is 0.40. $p = .18$ tons/sq.ft. (for a 3-ft excavation, from +23 to +20) by .61 = .11 tons/sq.ft. $\Delta p = 0.16$ tons/sq.ft. (for a 4-ft fill, from +23 to +27) by .61 = .10 tons/sq.ft.

The reduced pressure intensities due to the basement compared to Appendix C are $p_\gamma = 1.06 - .11 = 0.95$ tons/sq.ft. and $\Delta p_\gamma = 0.96 - .10 = 0.86$ tons/sq.ft. The settlement is 4.64 inches.

Stratum IV

$p_\gamma = 1.35 - 0.07 = 1.28$ tons/sq.ft. $\Delta p_\gamma = 0.85 - 0.06 = 0.79$ tons/sq.ft. The settlement is 2.88 in.

Thus the total settlement when the basement is in position = 0.62 + 4.64 + 2.88 inches = 8.14 inches. The original estimated settlement at the centre for the total design load is 10.57 in. The reduction in settlement resulting from the construction of the basement is 10.57 − 8.14 = 2.43 inches.

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