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" Settlement analyses of six structures in Chicago and London " †

by

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Mr E. M. Hayward (Chief Engineer, Trollope & Colls Ltd, London) stated that whilst he fully appreciated the value of such records of settlements of buildings, a word of warning should be given to those who might be induced by such instances of occasional settlements to reduce drastically permissible foundation pressures, which were the result of the accumulation of building experience in a particular locality. There was evidence of such a tendency in London.

It had been customary 20 to 30 years ago to design foundations for a gross pressure of 3 to 4 tons/sq. ft on the upper layers of the London blue or grey Clay. Admittedly the buildings were to carry greater live loads than customary today and which might not have been realized in practice, but they showed no sign of settlement of several inches as usually forecast. Today, however, Local Authorities were reluctant to permit more than about 2½ tons/sq. ft on that clay. The Institution Code of Practice No. 4 on Foundations recommended pressures lower than those previously adopted. Skempton [29] had suggested a pressure of about 2 to 2½ tons/sq. ft on London Clay for modern buildings of ten to twelve storeys. What practical justification was there for such a reduction? Were engineers being unduly influenced by the publication of such articles describing a ¾-in. settlement of a small building at Elstree under a pressure of about 1 ton/sq. ft on firm brown clay? Had the Authors considered any other reasons for that insignificant settlement? Had they checked any other buildings in the same locality?

There were numerous buildings in London designed for 2 tons/sq. ft on similar brown clay, which had been behaving quite satisfactorily for many years.

Mr Hayward referred to an office building which had five storeys and was steel-framed with foundations designed for 3¾ tons/sq. ft. It had been built about 16 years ago and was flanked on two sides by old brick buildings built about 50 to 100 years ago. At two levels stone string courses had been bonded to the adjacent older buildings. Those bondings had not cracked. Theoretically the settlement of the flanking buildings should have reached equilibrium but the new building should have settled about 1 to 3 in. It evidently had not settled and a walk round the City of London would provide numerous similar examples of new buildings bonded to older buildings or built tight against them without

† Proc. Instn Civ. Engrs, Part I, vol. 4, p. 525 (July 1955).

any signs of distress. Mr Hayward had knowledge of many important buildings constructed in the London area during the past 30 years. They had been built on London brown, grey, and blue Clay with gross foundation pressures between 2 and 4 tons/sq. ft. No serious settlements had occurred. Could the Authors give instances of modern buildings in London which had settled appreciably?

Many engineers could give examples of new extensions to existing buildings. In his experience the floors of the new buildings had invariably been made level with the existing buildings and no allowance was made for relative settlements. No noticeable settlement had occurred in such cases. What did the Authors think was the reason for that apparent discrepancy between theory and practice?

In the words of Terzaghi "it is obvious that the results of a settlement computation are not even approximately correct unless the assumed hydraulic boundary conditions are in accordance with the drainage conditions in the field." If the settlement constants were computed from a laboratory experiment with the sample held between porous plates, Mr Hayward suggested that that did not represent the true hydraulic boundary conditions of the foundations of a new building adjacent to or surrounded by existing buildings. If the surrounding clay was already stressed by existing buildings, the pore-water under the new building could not be forced into the pores of the adjoining sites unless the pore-water pressure under the new building was appreciably greater than the pore-water pressure in the clay under the adjacent buildings. Was that a possible explanation of why new buildings in built-up areas did not appear to settle so much as forecast?

Tattersall, Wakeling, and Ward [30] had stated:—

> "Undrained triaxial compression tests made on pairs of 1½-in.-dia. samples extracted from 4-in.-dia. cores taken from 80 to 100 ft depth were generally less than one-third the strength of samples obtained from the tunnel and trimmed by hand. Even at a depth of only 40 ft at this site the tests on cored samples probably underestimated the strength considerably. The material was too hard for core samples to be undisturbed."

Meyerhof and Murdock [31] had observed that there was significant decrease in the compressive strength of samples which had been stored in tubes for several days. They stated that:—

> "This decrease in strength, which amounted up to about one half of the original strength, was particularly noticeable for the stiffer and harder material and may be explained by the gradual opening of fissures of the clay after sampling."

The usual laboratory triaxial tests obviously gave results for London Clays lower than the real strengths of the clays in their undisturbed state. The factor of safety of 2½ suggested by Skempton [29] and the Code of Practice was probably too high and there seemed insufficient justification for taking only 2 to 2½ tons/sq. ft pressure on London Blue Clay. Probably the laboratory estimates of elastic modulus and coefficients of consolidation were also unreal, which might account for the fact that buildings in London generally did not settle so much as expected from theoretical computations.

It would be remarkable if a simplification such as equation (1) gave anything but an approximation to the correct answer to problems connected with such a heterogeneous anisotropic material as soil. In the synopsis the Authors had bravely stated that "settlements can be computed with errors not exceeding the limits of −30% and +50%." In Table 2 by an unfortunate selection of case histories those wide limits were reduced to an average "only 9% greater than the observed value." In view of the many assumptions governing the basic equation, it would be almost a fluke if the correct answer was given to within 9%. It might be ungenerous, but he could not help wondering whether it was possible for a little wishful thinking to choose or adjust the constants of the computations to give an anticipated result? Engineers were familiar with the use of dynamic pile-driving formulae alleged to give the static load bearing capacity of a pile and in which small alterations in the constants would give the anticipated or desired answer.

He welcomed the recording of factual observations as given in the Paper, but until far more than those few case histories were available it was advisable to accept Terzaghi's warning that "the computation of the rate of settlement has the character of a crude estimate." The Authors wisely acknowledged the limitations of their theories in their statement that "Theoretical considerations of this problem are difficult and have not yet been completed." Mr Hayward suggested that those few records of settlements were no valid reason for lowering the permissible foundation pressures, which had been established as safe and satisfactory by long experience of building in any locality.

Mr J. K. Alderman (Lecturer in Civil Engineering, Manchester University) observed that, on examining the time/settlement curves for the six structures analysed, it was difficult to understand why the Authors advocated the use of the equation:

$$\rho_f = \int_0^z m_v \,.\, \Delta\sigma \,.\, dz \qquad \ldots \qquad (1)$$

for the net final settlement of a foundation, and did not consider the use of the more fundamental equation for the net final settlement:

$$\rho_{\text{final}} = \rho_i + \rho_c \qquad \ldots \qquad (2)$$

where ρ_i denoted the immediate settlement $= q_n \,.\, B\frac{(1 + \nu^2)}{E} I\rho$

and ρ_c ,, the consolidation settlement $= \int_0^z m_v \,.\, \Delta\sigma \,.\, dz\ (= \rho_f)$,

together with the corresponding equation for the net settlement ρ_t at any time, t,

$$\rho_t = \rho_i + U\rho_c \qquad \ldots \qquad (3)$$

The time/settlement curves for the six structures had been calculated using equation (3) and it was found that for all the Chicago structures the recalculated curves were closer to the observed time/settlement curves than any of the calculated values given by the Authors (see Fig. 8). For the structure of the Fire Testing Station, Elstree, the recalculated curve overestimated the settlement by about 25%, but it should be noted that the field settlements had been observed only for 4 years and were still on the linear part of the settlement/$\sqrt{\text{time}}$ curve. It was therefore possible that after a further time the observed settlements might cross over the Authors' calculated curve.

It had been found impossible to recalculate the time/settlement curves for Waterloo and Chelsea Bridges since the divergence with time between the two methods of calculation could not be understood. Using the previously defined symbols then:

$$\begin{aligned}\rho_t \text{ (calculated by Authors)} - \rho_t \text{ (conventional)} &= \{\rho_i + U(\rho_c - \rho_i)\} - \{U \,.\, \rho_c\} \\ &= \rho_i(1 - U)\end{aligned}$$

The difference between the two calculated values should be convergent as the time increased. Figs 3 and 4 in the Paper, however, showed the two curves were divergent with time.

The method of calculation for the net settlement at any time t suggested by the Authors and given in the equation:

$$\rho_t = \rho_i + U(\rho_c - \rho_i) \qquad \ldots \qquad (4)$$

also broke down if $\rho_i > \rho_c$. The Authors had not mentioned that possibility and in fact stated that "the net final settlement is typically between two and six times the settlement at the end of construction." It had been found, however, during settlement calculations for the analysis of structures on glacial clays in Lancashire that $\rho_i > \rho_c$ and that the settlement at the end of construction was about 60% of the net final settlement (Fig. 9). No full-scale site observations were yet available to confirm the above analysis, but model

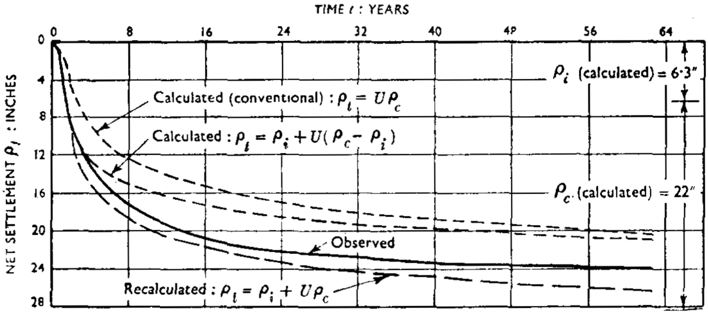

FIG. 8.—AUDITORIUM TOWER, CHICAGO

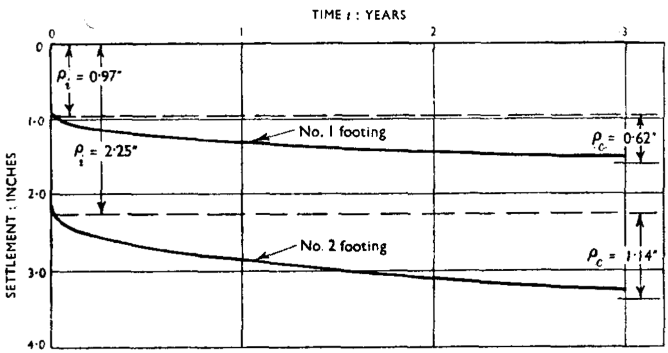

FIG. 9.—SETTLEMENT OF FOUNDATIONS ON GLACIAL CLAY

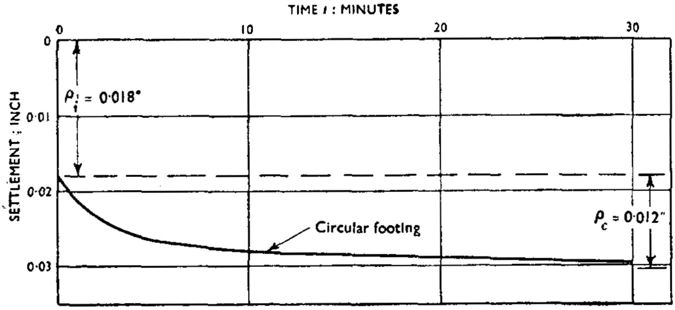

FIG. 10.—SETTLEMENT OF MODEL FOOTINGS

footing tests on undisturbed samples from the field had shown that the immediate settlement ρ_i was greater than the consolidation settlement. Fig. 10 showed the time/settlement curve for a model footing test on a typical undisturbed sample from the site analysed in Fig. 9, from which it could be seen that in both cases the ratio $\rho_i/\rho_c = 1{\cdot}5 - 2{\cdot}0$. If that value was substituted in equation (4) the settlement at any time t was found to decrease as the time increased. It was therefore suggested that until full-scale site observations were available equations (2) and (3) should be used for estimating the settlement of foundations in Lancashire glacial clays.

Professor G. G. Meyerhof (Head, Department of Civil Engineering, Nova Scotia Technical College, Halifax, N.S., Canada) considered that the net settlement at any time could, in addition to the two methods mentioned by the Authors (equations 4 and 5) also be estimated from the equation

$$\rho_t = \rho_i + U\rho_{\text{final}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where ρ_i denoted the net immediate settlement (equation 2), ρ_{final} the final consolidation settlement (equation 1), and U the degree of consolidation.

That equation was based on a theoretical approach,[32] whereas the Authors' equation (5) was of a semi-empirical nature.

Using equation (6) the calculated rates of settlement agreed somewhat better with the observed movements of the six structures, especially at Chicago, than did the Authors' equation (5). Whilst at the end of the construction equations (5) and (6) gave practically the same result for the net settlement, equation (6) overestimated the final net settlement, as had been mentioned by the Authors, the mean ratio of calculated/observed final settlement for the six structures being 1·4 (using equation 6) compared with 1·1 (using equation 5). On balance it might therefore be concluded from an analysis of the present cases that there was little to choose between equations (5) and (6) and both equations were definitely superior to the conventional equation (4) as was stated by the Authors.

Professor Skempton, in reply to Mr Hayward, wished to make it clear that the Paper did not deal with allowable settlements of buildings, but with the records of six structures for which both settlement calculations and observations were available in some detail. And those records had shown that the method of settlement computation at present in use gave results which were substantially correct. Moreover, in another Paper,[33] it had been shown that, so far as final settlements were concerned, that conclusion was valid for a total of twenty structures in various parts of the world. Much had still to be learnt, however, and Mr Hayward could be assured that work was actively proceeding to improve the methods of settlement calculation.

Mr Hayward evidently felt that, in London Clay, soil tests were unreliable and computations severely overestimated settlements. But for the three structures on that Clay, described in the Paper, the calculated final settlement was, on the average, only 33% in excess of the actual value; and at the time of the latest recorded settlement the error was less than 20%. At the new Government Offices in Whitehall the maximum settlement two years after completion of the building was 1·4 in., compared with a calculated value of 1·5 in.[34]

In the past it seemed often to have been thought that because there were no cracks in a building, it had not settled or, at least, that the settlements were not appreciable. Yet there were many buildings on clay which had undergone maximum settlements of 3 or 4 in. but which had shown no signs of any cracking. Therefore it was unjustifiable to assume that little if any settlement had occurred simply because a building was not cracked or visibly distorted.

It was true, as Mr Hayward had pointed out, that there were many buildings in London erected immediately alongside older buildings, with string courses lined up with, or even bonded into, the adjacent structures; and yet no visible differential settlement had occurred. A probable explanation was simply that the clay under the new building was pre-composed by the old building which had been demolished to make way for the new structure which, in many cases, imposed no load on the clay additional to that which had been there before. Indeed, with modern structures, the weight might be less. Therefore the settlement of the new building would be very small and comparable in magnitude to the elastic recovery of the clay when the old building had been removed.

With regard to the allowable pressures on London Clay, although that matter was outside the scope of the Paper, Professor Skempton considered that his recent statement to the effect that 2 to 2½ tons/sq. ft was suitable for the footings of modern blocks of flats represented no departure from accepted practice. Those buildings usually had no basements, and the footings were typically about 8 or 10 ft below ground surface. In the outer regions of London that depth was, in most cases, still well within the zone of the brown clay, on which higher pressures had rarely been used. In fact, Mr Hayward had implied that a pressure of 2 tons/sq. ft was common on the brown clay. The settlement of ¾ inch at Elstree under a pressure of 1 ton/sq. ft could hardly have led to a decision to reduce the allowable pressures on the brown clay, since, as Mr Hayward himself had pointed out, that settlement was insignificant.

In reply to Mr Alderman and Professor Meyerhof there could be no doubt that the equations

$$\rho_{\text{final}} = \rho_i + \rho_c$$

and

$$\rho_t = P_i + U \, . \, \rho_c$$

were correct. The problem, however, was how to determine ρ_c. Mr Alderman and Professor Meyerhof had both suggested that

$$\rho_c = \int m_v \, . \, \Delta\sigma \, . \, d_z$$

but, as the Authors had stated on p. 528 of the Paper, that assumption was not generally true. In fact, it was more nearly correct to say that

$$\rho_{\text{final}} = \rho_i + \rho_c = \int m_v \, . \, \Delta\sigma \, . \, d_z$$

The oedometer test measured the compressibility of the clay under increasing vertical stress with no lateral movement. In contrast, the ground under a foundation was subjected to shear stress (as well as vertical stresses); there were lateral movements and pore pressures set up when the foundation load was first applied were, in general, very different from those set up when the load was applied to an oedometer specimen.

A rigorous treatment of the problem would require complex triaxial testing in two stages, firstly to measure the properties of the clay relevant to immediate settlement, followed, secondly, by measurement of the subsequent volume changes during consolidation. To relate the problem to present technique, however, the following treatment might be helpful.

If the settlement, as determined from the oedometer test was denoted by ρ_{oed} where, as usual, $\rho_{oed} = \int m_v \, . \, \Delta\sigma \, . \, d_z$ and if the true consolidation settlement $\rho_c = S \, . \, \rho_{oed}$ where S was a factor depending, primarily, on the compressibility ratio of the clay[35] which, in its turn, depended chiefly on the geological history of the clay, then:

$$\rho_{\text{final}} = \rho_i + S \, . \, \rho_{oed}$$

and

$$\rho_t = \rho_i + U \, . \, S \, . \, \rho_{oed}$$

Theoretical considerations showed that for normally-consolidated clays S was a little less than 1·0, whilst for over-consolidated clays the value was roughly 0·5, or even less if the clay had been heavily over-consolidated.

Those conclusions were in broad agreement with the observations reported in the Paper; and the "recalculated" curve, plotted in Fig. 8 by Mr Alderman for the Auditorium Tower, was an example of the case $S = 1$ for normally consolidated clay, as was the analysis by Professor Meyerhof.[32] Dr L. Bjerrum and Professor Skempton were hoping to publish the theoretical work within the coming year. But, for the present, the widely adopted assumption that $\rho_{\text{final}} = \rho_{oed}$ could continue to be used, as an approximation, since it was known to give results not differing from field observations by more than 50% in the great majority of clays and involved only the simplest testing and computational procedure. The Authors were glad that Professor Meyerhof agreed with their conclusion that the conventional method of calculation, as represented by equation (4), was definitely inferior to the procedure used in the Paper.

FURTHER REFERENCES

29. A. W. Skempton, "Foundations for high buildings." Proc. Instn Civ. Engrs, Pt III, vol. 4, p. 246 (Aug. 1955).
30. Fred Tattersall, T. R. M. Wakeling, and W. H. Ward, "Investigations into the design of pressure tunnels in London Clay." Proc. Instn Civ. Engrs, Pt I, vol. 4, p. 400 (July 1955).
31. C. G. Meyerhof and L. J. Murdock, "An Investigation of the Bearing Capacity of Some Bored and Driven Piles in London Clay." *Géotechnique,* vol. III, p. 267 (1952–53).
32. G. G. Meyerhof, "The tilting of a large tank on soft clay." Proc. South Wales Inst. Engrs., 1951, vol. 67, p. 53.
33. D. H. MacDonald and A. W. Skempton, "A Survey of Comparisons between Calculated and Observed Settlements of Structures on Clay." Proc. Conf. Correlation between Calculated and Observed Stresses and Displacements in Structures, 1955, pp. 318–337.
34. G. G. Meyerhof, "Some Recent Foundation Research and its Application to Design." Struct. Eng., 1953, 31, 151–167.
35. A. W. Skempton, "The Effective Stress in Saturated Clays strained at Constant Volume." Proc. Seventh Int. Cong. Appl. Mech., 1948, vol. 1, p. 378.