A Theoretical Examination of Errors in Measured Settlements of Test Piles

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SUMMARY - A theoretical examination is made of the errors involved in settlement measurements on a test pile, using various loading and measurement systems. Correction factors are derived which may be applied to the measured settlement in order to obtain a better estimate of the true settlement of the test pile. It is found that the errors involved in using ground anchors are generally considerably less than those associated with the use of a reference beam for measuring settlement or in jacking the test pile against adjacent anchor piles. If the latter type of loading system is used, the errors in the measured settlement may be reduced by measuring the settlement with reference to the anchor piles rather than a distant reference point.

On the basis of the theoretical solutions, recommendations are made regarding the minimum desirable spacing between the test pile and reference beam supports, the test pile and adjacent anchor piles or the test piles and the supporting ground anchors.

1 INTRODUCTION

There is an increasing tendency to use pile load tests as a basis for predicting the ultimate load capacity and settlement of pile foundations (Refs.5 and 6). Until recently, the measurement of settlement was often considered to be of secondary importance but it is now recognized that settlement measurements on a single test pile may be used to predict the settlement of a pile group from theoretical considerations (Refs. 1 and 2). However, some of the more commonly used methods of settlement measurement and loading of test piles may influence the settlement of the pile and give misleading data. In this paper, an examination is made of three of these methods and of the errors involved in the measured settlement of the test pile. These errors are evaluated from pile settlement theory derived from elastic analyses, and apply to measured settlements at normal working loads (up to about one-half the ultimate load of the pile). The results of the evaluation are presented in terms of correction factors which may be applied to the measured settlement to obtain a better estimate of the true settlement of the pile. The relative merits of the three systems of measurement and loading are discussed and recommendations are made regarding desirable spacings between the test pile and the supports for loading or settlement measurement.

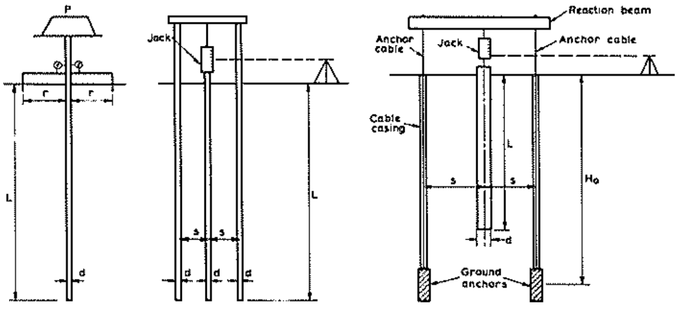
2 LOADING AND SETTLEMENT MEASUREMENT SYSTEMS EXAMINED

The following test procedures are examined herein:

(a) the use of a reference beam to measure the settlement of the pile (Fig.1a). The test load is assumed to be applied by kentledge.

(b) the use of two anchor piles to provide reaction for the test load (Fig.1b). Two methods of settlement measurement are considered, measurement of the pile head movement by level from a remote point, or measurement of the settlement of the test pile with reference to the reaction piles.

(c) the use of ground anchors to provide reaction for the test load. The pile settlement is assumed to be measured by level from a remote point (Fig.1c).



(a) Settlement Measurement Using Reference Beam
(b) Test Pile Jacked Against Reaction Piles
(c) Test Pile Jacked Against Ground Anchors

Fig. 1 Pile Load Test Arrangements.

3 ERRORS DUE TO USE OF REFERENCE BEAMS

With this system of settlement measurement, the reference beam supports settle due to the loaded pile. A theoretical assessment of the resulting errors in the measured settlement may be made by using the solutions for the settlement of a point on the surface of the soil due to a loaded cylindrical pile (Ref.3). At any point, this settlement ρ_s may be expressed as

$$\rho_s = \frac{P}{LE_s} I_\rho \qquad (1)$$

where P = applied load on pile
L = pile length
E_s = Young's modulus of soil (assumed constant with depth)
I_ρ = displacement influence factor.

I_ρ is a function of the position of the point relative to the pile, the ratio of length L to diameter d of the pile and the stiffness of the pile relative to the soil, which can be expressed as a pile stiffness factor K, where

$$K = \frac{E_p}{E_s} \cdot R_A \qquad (2)$$

where E_p = Young's modulus of pile
R_A = area ratio of pile
= ratio of area of pile section to gross cross-sectional area of pile (R_A = 1 for a solid pile).

Values of I_ρ for a wide range of parameters have been evaluated (Ref.3).

The true settlement ρ_t of the loaded pile itself may be expressed as

$$\rho_t = \frac{P}{dE_s} \cdot I \qquad (3)$$

where I = pile settlement factor, a function of L/d, K and the nature of the pile (i.e. floating or end-bearing).

Solutions for I are given in Ref.4.

The measured settlement, ρ_m, of the pile head is therefore

$$\rho_m = \rho_t - \rho_s$$

$$= \frac{P}{dE_s}\left(I - I_\rho \frac{d}{L}\right) \qquad (4)$$

It is convenient now to define a correction factor F_c to be applied to the measured settlement ρ_m to obtain the true settlement ρ_t i.e.

$$\rho_t = F_c \cdot \rho_m \qquad (5)$$

From Eqs.3, 4 and 5,

$$F_c = \frac{I}{I - \frac{d}{L} I_\rho} \qquad (6)$$

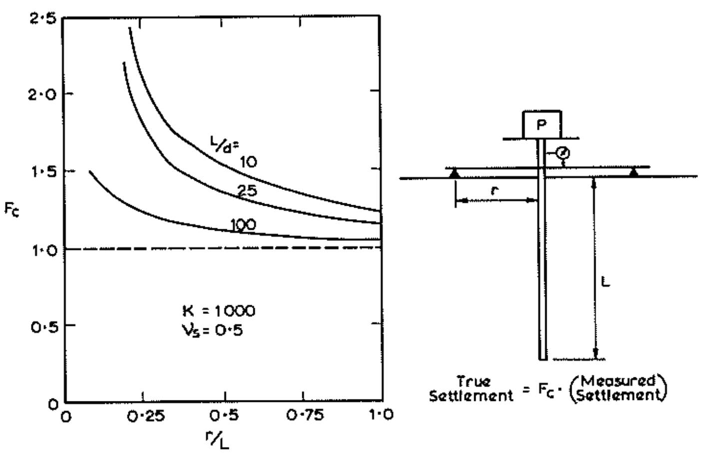


Fig.2 Correction Factor F_c For Floating Pile in Deep Layer of Soil.

F_c is plotted in Figs.2 and 3 for the cases of a floating pile in a deep layer and in a layer of finite depth. Fig.2 indicates that serious errors (i.e. large values of F_c) may arise in settlement measurements on a test pile in a deep soil layer unless each support of the reference beam is placed about 0.5 to 1 pile length away from the pile. For a pile of given length, the error becomes more severe as the diameter increases (i.e. L/d decreases). Fig.3 shows how the effect of the support beam movement diminishes with decreasing soil layer thickness. However, even for an end-bearing pile (H/L =]), the results indicate that it is desirable to have the supports 0.3 to 0.5 pile lengths away from the test pile.

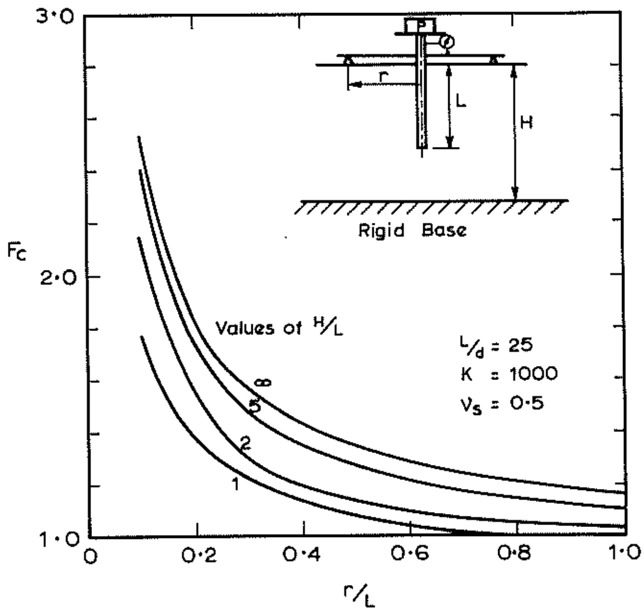


Fig.3 Effect of Layer Depth on Settlement Correction Factor F_c.

4 ERRORS DUE TO JACKING AGAINST ANCHOR PILES

With this method of load application, the upward loads on the anchor piles cause an upward movement of the test pile. As a result, if the settlement of the test pile is measured from a remote point, the measured settlement will be less than the true value. A theoretical examination of the errors involved may be made by using solutions for the settlement interaction between two piles in an elastic mass (Refs.1 and 2).

The true settlement ρ_t of the test pile is again given by Eq.2. The upward movement $\Delta\rho$ of the test pile due to the reaction on the anchor piles may be expressed as

$$\Delta\rho = \frac{2\,P/2.I.\alpha_1}{dE_s} \qquad (8)$$

where α_1 = interaction factor for two piles at a spacing s, where s is the centre-to-centre distance between the test pile and each reaction pile.

The value of α_1 is a function of dimensionless pile spacing s/d L/d, K and the nature of the pile and is graphed and tabulated for a wide range of cases (Ref.2).

The measured settlement ρ_m is therefore

$$\rho_m = \rho_t - \Delta\rho$$

$$= \frac{PI}{dE_s}(1-\alpha_1) \qquad (9)$$

Defining the correction factor F_c as in Eq.6, it is found from Eqs.2 and 9 that

$$F_c = \frac{1}{(1-\alpha_1)} \qquad (10)$$

Values of F_c for a floating pile in a deep soil layer are shown in Fig.4. The test pile and anchor piles are assumed identical. In the range of spacings commonly used (2.5 to 4 pile diameters), F_c may be 2 or more i.e. the measured settlement may be less than half the true settlement. The error becomes more severe for stiffer or more slender piles. Backfiguring the soil modulus from the uncorrected measured settlement will result in too high a modulus and hence too low a settlement prediction for the pile foundation.

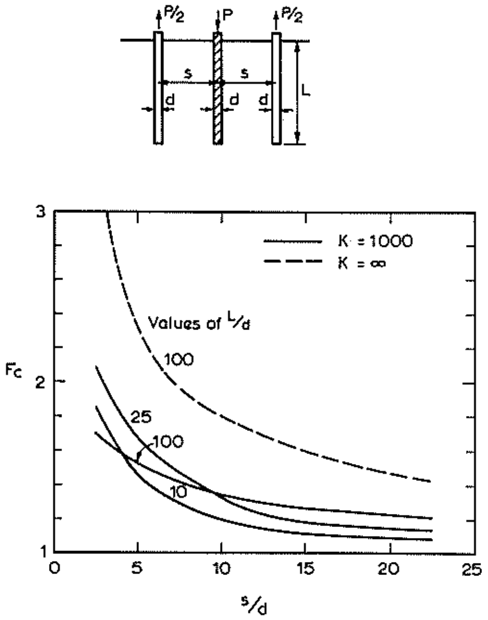


Fig.4 Correction Factor F_c Floating Pile in a Deep Layer Jacked Against Two Reaction Piles.

Fig.5 shows values of F_c for end-bearing piles resting on a rigid stratum. In this case, the interaction is generally much less and consequently F_c is only significantly larger than unity if the piles are relatively slender and compressible. Fig.6 shows the effect on F_c of the relative stiffness of the bearing stratum E_b/E_s (E_b = Young's modulus of bearing stratum). As the bearing stratum becomes stiffer, interaction decreases and hence F_c decreases for a given pile spacing.

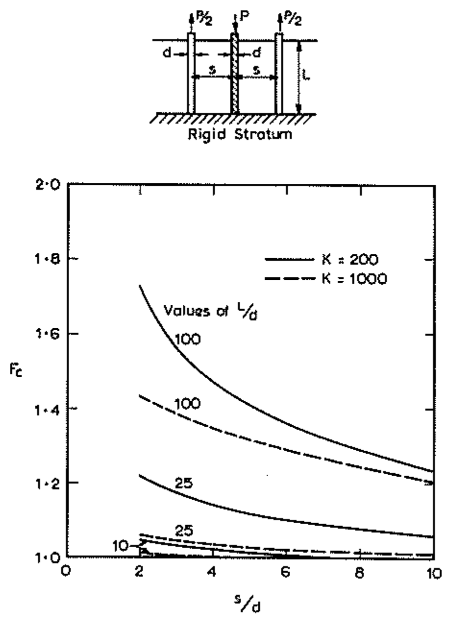


Fig.5 Correction Factor F_c for End-Bearing Pile on Rigid Stratum Jacked Against Two Reaction Piles.

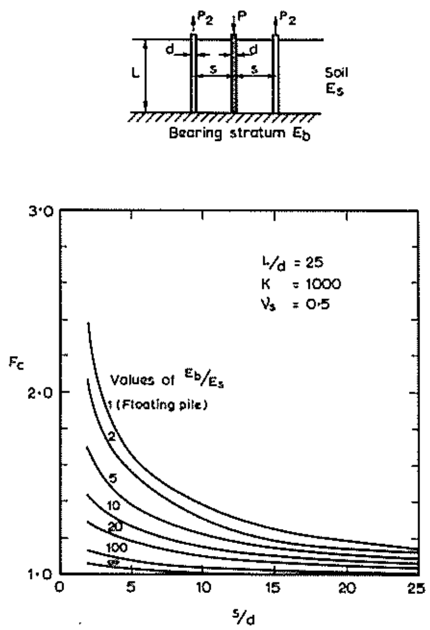


Fig.6 Correction Factor F_c.Effect of Bearing Stratum for End-Bearing Pile Jacked Against Two Reaction Piles.

An alternative means of settlement measurement is possible with the anchor pile system by measuring the settlement of the test pile with reference to the reaction piles e.g. by fixing a dial gauge to the cross beam joining the anchor piles. The upward movement of each reaction pile, ρ_a, can be expressed as

$$\rho_a = \frac{P/2\ I}{dE_s} - \frac{P\ I\alpha_1}{dE_s} + \frac{P/2\ I\alpha_2}{dE_s}$$

$$= \frac{PI}{dE_s}(0.5 - \alpha_1 + 0.5\alpha_2) \qquad (11)$$

where α_1 = interaction factor for two piles at a spacing of s, and α_2 = interaction factor for two piles at a spacing of 2s.

The settlement of the test pile relative to the reaction piles, ρ'_m, is then

$$\rho'_m = \rho_m + \rho_a$$

$$= \frac{PI}{dE_s}(1.5 - 2\alpha_1 + 0.5\alpha_2) \qquad (12)$$

Defining a modified correction factor F'_c as

$$F'_c = \frac{\text{true settlement of test pile}}{\text{measured settlement of test pile relative to anchor piles}} \qquad (13)$$

it may be shown from Eqs.2, 12 and 13 that

$$F'_c = \frac{1}{(1.5 - 2\alpha_1 + 0.5\alpha_2)} \qquad (14)$$

Values of F'_c are plotted against dimensionless spacings s/d in Fig.7 for a floating pile in a deep soil layer. Comparison with Fig.4 shows that F'_c is generally less than F_c i.e. less correction of the measured settlement is required if movement is measured with respect to the anchor piles. For piles of medium compressibility (K=1000), F'_c is about unity at a spacing of about 5 diameters. It must be pointed out however that at larger spacings or in situations where little interaction is likely to occur between the test pile and anchor piles, F_c' will be less than 1 i.e. the measured settlement will be greater than the true settlement. In such cases, the soil modulus backfigured from the uncorrected measured settlement would be too small in contrast to the value obtained from the settlement measured from a remote point. Thus, measurement of the test pile settlement relative to the reaction piles would appear to have an advantage in that it gives a settlement either closer to or larger than the true settlement. However, in any such pile test, measurement of the settlement by both the alternative methods is desirable so that a better assessment of the true settlement may be made.

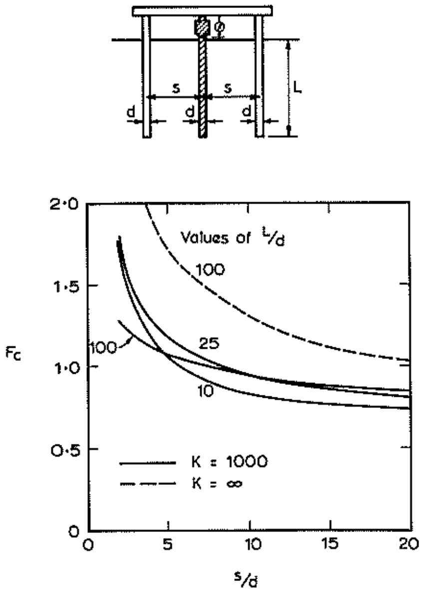


Fig.7 Correction Factor F_c. Floating Pile in a Deep Layer Jacked Against Two Reaction Piles-Settlement Measured in Relation to Anchor Piles.

5 ERRORS DUE TO JACKING AGAINST GROUND ANCHORS

The upward reaction on each ground anchor will tend to reduce the settlement of the test pile. Because the cables for the ground anchors are generally cased and the anchors themselves are small in relation to the test pile, it is reasonable to approximate each anchor as an upward point load acting at the centre of the anchor. To simplify calculations it is then assumed that the effect of the ground anchor on the test pile is the same as its effect on a point located half way along the pile. With the above approximations, the upward movement $\Delta\rho$ of the test pile due to the ground anchors can be written as

$$\Delta\rho = \frac{2\ P/2}{E_s\ L} \cdot I_M \qquad (15)$$

where I_M = vertical displacement factor for a buried point load.

I_M may be evaluated most readily from Mindlin's equation for a point load within a semi-infinite elastic mass.

The true pile settlement ρ_t is again given by Eq.3, so that the measured settlement ρ_m of the test pile is

$$\rho_m = \frac{P}{E_s d}\left(I - I_M \cdot \frac{d}{L}\right) \quad \ldots\ \ldots\ \ldots \quad (16)$$

Defining the correction factor F_c as in Eq.6,

$$F_c = \frac{1}{\left(1 - \frac{I_M}{I} \cdot \frac{d}{L}\right)} \qquad (17)$$

F_c is plotted against dimensionless anchor spacing in Fig.8 for various values of embeddment of the anchors. The test pile and the anchors are assumed to be in a deep layer. Fig.8 shows that if the anchors are located 1.5 pile lengths or more below the surface, F_c is less than 1.2 i.e. the error in the measured settlement is less than 20%. Beyond an anchor depth of about 2L, the radial distance of the anchors from the pile has little effect on the measured settlement.

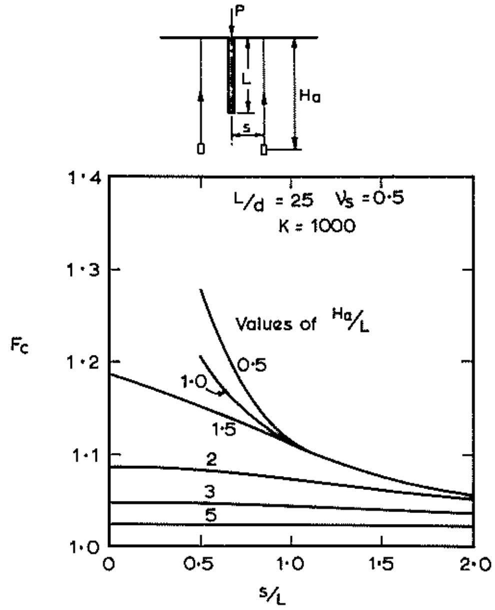


Fig.8 Correction Factor F_c. Floating Pile in a Deep Layer Jacked Against Ground Anchors.

The case considered in Fig.8 is not likely to occur frequently in practice since to obtain adequate load capacity, the anchors are usually secured into a stiffer layer at or below the level of the pile tip. In such a case, the upward movements due to the anchors would be less than given by Eq.15, so that F_c will be less than indicated in Fig.8.

Fig.8 will also generally give an overestimate of F_c for an end-bearing test pile bearing on a stiff layer. The extreme case of a pile through very soft soil and bearing on a stiff layer may be examined by considering the pile tip as a rigid circular area carrying the total applied load and the anchors as point loads acting on the surface of a semi-infinite mass of modulus E_b (the bearing stratum). For this case, F_c is plotted in Fig.9 together with the other limiting case of a pile in a homogeneous deep layer with anchors at the level of the pile tip (the curve for H_a/L = 1.0 in Fig.8). It may be seen that when the pile bears on to very stiff rock through very soft soil, ($E_b/E_s \to \infty$), F_c is extremely small even for very closely spaced anchors, whereas the corresponding value for the homogeneous layer (E_b/E_s = 1) is considerably greater. In practice, the value of F_c would lie between these two limiting values.

Fig.9 indicates that when anchors are to be fixed at the level of the pile tip, the spacing between the test pile and the anchors should be as great as possible and preferably 10 diameters or greater. Greater spacings may be achieved most readily by installing inclined anchors.

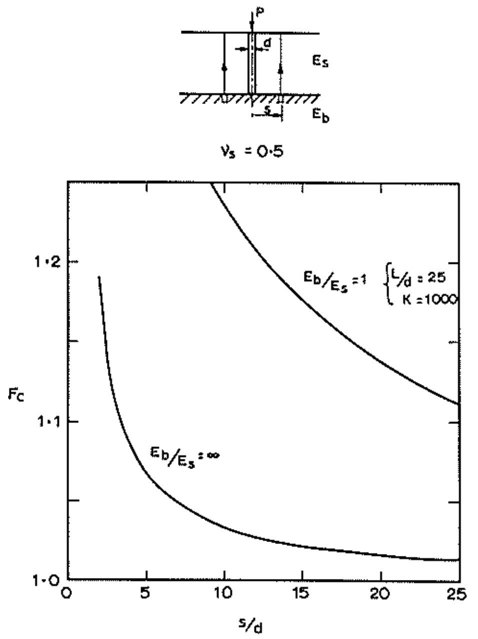


Fig.9 Correction Factor F_c End-Bearing Pile Jacked Against Ground Anchors.

Comparisons with the other two test systems shows that F_c for the anchor system is generally much less i.e. less error is involved in settlement measurements when anchors are used.

6 DISCUSSION AND CONCLUSIONS

The correction factor F_c indicates the error in the measured settlement of a test pile with a particular loading and measurement system; the greater the divergence of F_c from unity, the greater is the error. The systems examined, with one possible exception, give a measured settlement which is less than the true settlement and hence may lead to an underestimate of the foundation settlement. In order that the errors in the measured settlement should not exceed 20%, the following conditions appear to be desirable:

(a) when a reference beam is used for measuring settlement, each support of the reference beam should be placed at least 0.5 pile lengths (and preferably more) from the centre of the test pile if it is situated in a relatively deep soil layer, or about 0.3 to 0.5 pile lengths away if the test pile is an end-bearing pile.

(b) when the test pile is jacked against reaction piles and the settlement is measured from a remote point, the spacing between the test pile and each reaction pile should be no less than 5 diameters and possibly 10 diameters or more for long floating piles.

(c) when the test pile is jacked against reaction piles and the settlement is measured with reference to the reaction piles, the error in the measured settlement is less than in (b) above, and a spacing of 5 pile diameters between the test pile and each reaction piles may be sufficient.

(d) when the test pile is jacked against ground anchors, a spacing between the test pile and each anchor of about 10 pile diameters will generally be adequate and smaller spacings may be used for end-bearing piles.

The theoretical calculations indicate that the errors involved in the use of ground anchors are considerably less than those associated with the other systems. If the use of an alternative system is unavoidable, efforts should be made to minimize the errors involved in the measured settlement and to allow for these errors to obtain a better indication of the true settlement characteristics of the pile. The theoretical solutions presented herein provide some basis for such an allowance, bearing in mind always the limitations of the idealized situations examined theoretically. Possibly the main value of the calculations is to indicate the order of magnitude of the error in measured settlement and to suggest more appropriate procedures than are now in common use.

7 ACKNOWLEDGMENTS

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