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Structure-Foundation Interaction and Soil Creep

L'Interaction entre une Structure et Ses Fondations Causée par le Fluage de la Terre

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SYNOPSIS An examination of the effect of soil creep on structure-foundation-soil interaction with regard to variation of differential settlement of columns, bending moments in the structure and column loads is presented. The structures considered are three-bay portal frames with pin-based columns, the foundations considered are strip footings of finite length, and the soil is regarded as being a linear visco-elastic continuum of infinite depth. The adopted creep function is almost linear with log time and thus has the same general form as that commonly observed in Laboratory tests.

The purpose of the paper is to indicate, in terms of the relative stiffnesses of the structure, foundation and soil, which situations will lead to significant deterioration in conditions for the structure with elapse of time. The effects of changes in most of the parameters of the problem are discussed. Thus the results presented should enable estimates to be made of the changes in the various interaction effects with time, when the creep properties of the soil have been determined.

INTRODUCTION

When a frame building and continuous foundation rest on a soil for which creep effects are significant, the interaction between the various portions of the system will vary with time. For this reason the conditions to which the structure is subjected may become increasingly adverse and lead to some form of long-term structural distress.

The present paper does not aim to describe a method for carrying out interaction analyses including the effect of soil creep, or to provide a comprehensive set of graphs which would enable accurate results to be obtained without performing such analyses. Instead it presents the results for one form of structure for a wide range of relative stiffnesses of building, foundation and soil. The effects of changes in most of the parameters of the problem are then discussed, and it is hoped that this information will provide a useful basis for estimation of the various interaction effects in the structure and their variation with time.

At the time of application of the load due to the building being analysed, the soil mass must be undergoing creep settlement caused by load increases associated with the formation or prior loading of the deposit. However in most naturally occurring soil deposits, the prior loading has been applied so long ago that the magnitude of creep settlement due to this cause will be extremely small in the near future. For this reason

and for the sake of simplicity, creep settlement due to prior loading has been ignored in the present analysis, and only those settlements which arise due to the loading applied by the structure are considered.

Although the time taken to erect the structure will be finite, it has been assumed that this construction time is insignificant in comparison with the time periods being considered in the present analysis. On this basis, the settlements due to the structure are immediate settlement, consolidation settlement and creep settlement. For the purposes of the present analysis, settlement due to constant load was assumed to be proportional to the creep function $j(t) = A[1 + \beta \ln(1 + \alpha t)]$: Thus the assumed form of settlement variation with time is an immediate settlement, plus a settlement which increases in slope on a log time plot, until it becomes virtually linear with log time, and the settlement has the same form as that commonly observed in laboratory tests after the virtual completion of primary consolidation. Selection of suitable values for the parameters of the creep function will enable the appropriate immediate and creep settlements to be represented by the creep function. However the theoretical model will be unable to give a realistic representation of soil behaviour during the period when the major portion of the primary consolidation is taking place.

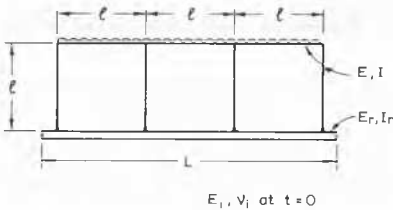


Fig. 1 The Problem Considered

THE ANALYSIS

The structures considered were three bay symmetrical plane portal frames with pin-based columns, and the length and stiffness of all beams and columns were assumed to be equal (see Fig.1). The beams were all subject to equal uniform loading and the frames were analysed by means of the expressions provided by Kleinlogel (1948). The foundations were strip footings of finite length, with a length/breadth ratio of 3, and were analysed using simple bending theory. The foundations were assumed to be unaffected by horizontal loads, and reaction pressures beneath the foundation were assumed to be vertical.

The soil was assumed to be a linear visco-elastic half-space. After simplification by application of a Laplace Transform $\bar{f}(s) = \int_0^{\infty} e^{-st} f(t)dt$, the stress-strain relationship for the soil takes the form

$$\{\bar{\sigma}\} = [\bar{D}] \{\bar{\epsilon}\} \dots \dots (1)$$

where $[\bar{D}]$ is the matrix of transformed elastic constants, and Equation (1) is analogous to Hooke's law for an elastic material.

The relationship between the creep function $J(t)$ and the soil properties can be seen by considering the solution of the Boussinesq problem of a vertical point load P_0 acting on the surface of an isotropic homogeneous half-space. The vertical surface deflection w at a distance R from the point of application of the load is

$$w(R) = \frac{1}{4\pi} \frac{3K+4G}{3K+G} \frac{P_0}{GR}$$

where K and G are the bulk modulus and shear modulus of the soil. If the correspondence principle is invoked to deduce the solution for a visco-elastic half-space subject to a point load $P(t)$, it is found that

$$\bar{w}(R) = \frac{1}{4\pi} \frac{3\bar{K}+4\bar{G}}{3\bar{K}+\bar{G}} \frac{\bar{P}}{\bar{G}R}$$

The variation of w with time can be found by inverting the Laplace transform, and for a constant load the solution will have the form

$$w(t) = \frac{P_0}{\pi R} J(t) \dots \dots (2)$$

where $J(t)$ is the inverse transform of $\frac{1}{4} \frac{3\bar{K}+4\bar{G}}{3\bar{K}+\bar{G}} \frac{1}{\bar{G}R}$. Now consider a circular area of radius a subject to a load distribution $\frac{P_0}{2\pi a^2} \frac{a}{\sqrt{a^2-r^2}}$ where r is the radial coordinate. Then it follows from the principle of super-position and Equation (2) that the deflection within the circular area is

$$w_{rigid}(t) = \frac{P_0}{2a} J(t) \dots \dots (3)$$

This demonstrates that $J(t)$ can be determined directly from a plate bearing test. It is interesting to note that Equations (2) and (3) also apply to a cross-anisotropic half-space.

The behaviour of the linearly elastic portion of the system, namely the building and foundation, was determined by equating displacements at the column bases, assuming that the ends of the footing were pinned. The behaviour of the whole system was then analysed by the method described by Brown and Booker (1976) using Laplace transforms.

The analysis was based on relative stiffnesses which were ratios of the stiffnesses of the building (K_b) and the strip footing (K_r) and the initial stiffness of the soil (K_s), and were defined as follows

$$K_b = \frac{nEI}{L^3}, \quad K_r = \frac{E_r I_r}{L^3}, \quad K_s = \frac{E_i}{1-\nu_i}$$

$$K_{rs} = K_r/K_s, \quad K_{sb} = K_s/K_b, \quad K_{br} = K_b/K_r$$

- n = number of storeys
- E = Young's modulus of structural material
- I = second moment of area of beams
- l = length of beams
- E_r = Young's modulus of footing material
- I_r = second moment of area of footing
- L = length of footing
- E_i = initial Young's modulus of soil
- ν_i = initial Poisson's ratio of soil

For the building and footing studied in detail $3l/L = 0.90$, and for the adopted creep function $\beta = 1$ and at ranged from

0 to 10, so that settlements at the surface of the soil increased to approximately three times their initial value.

DISCUSSION OF RESULTS

The results presented show variation of differential settlement, eaves moment and outer column load. The reference value of differential settlement of column bases was obtained by applying the column loads corresponding to zero differential settlement, to the foundation resting on soil in its initial condition and with no structure attached. Fig. 2 shows the ratio of actual differential settlement of column bases to the reference value of differential settlement. When the footing is flexible compared with the soil ($K_{RS} < 2 \times 10^{-4}$), differential settlement tends to increase in much the same way as total settlement increases (i.e. like $J(t)/J(0)$), unless restrained by the stiffness of the structure. However for larger values of K_{RS} , the increased footing stiffness tends to prevent significant increase in differential settlement with time and the consequent increase in the creep function.

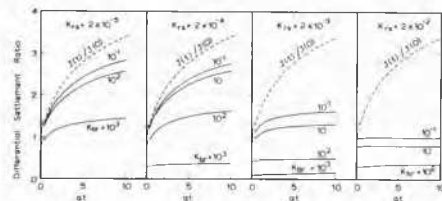


Fig. 2 Variation of Differential settlement of Column Bases

The differential settlement ratio shown in Fig. 2 is based on a different reference value for each value of K_{RS} , and consequently the graphs do not indicate the variation of differential settlement with continuous variation of relative stiffness of footing to soil. In fact when the other parameters are constant, differential settlement increases monotonically with decreasing soil stiffness, or with elapse of time, although the increase may be very small.

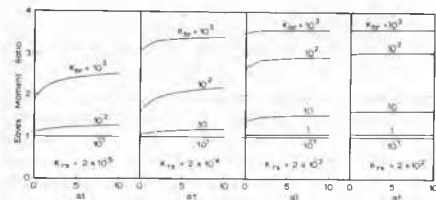


Fig. 3 Variation of Eaves Moment

Eaves moments are shown in Fig. 3 as the ratio of actual eaves moment to the eaves moment occurring when there is no differential settlement of the column bases. The eaves moment ratio increases monotonically with increasing relative stiffness of footing to soil, and with elapse of time. Because the eaves moment ratio is based on a single reference value, the magnitude of the eaves moment also increases monotonically with relative stiffness of footing to soil and with time. Outer column loads are shown in Fig. 4 as the ratio of actual outer column load to the outer column load occurring when there is no differential settlement. As in the case of eaves moment, both the outer column load ratio and the magnitude of the outer column load increase monotonically with increasing relative stiffness of footing to soil, and with time.

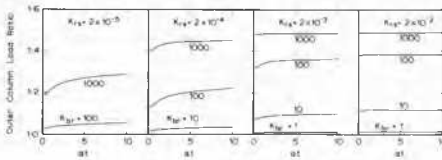


Fig. 4 Variation of Outer Column Load

When the structure is flexible compared with the footing ($K_{BR} < 1$), the changes in differential settlement which occur with increasing time cause little change in moment or column load. However with increasing K_{BR} , both eaves moment and outer column load can be seen to increase to values significantly larger than those applying when there is zero differential settlement. For the larger values of K_{RS} ($> 2 \times 10^{-3}$), elapse of time causes very slow increase in eaves moment or

outer column load since differential settlement is increasing very slowly.

For each value of K_{RS} , the results have the initial values which would be given by an elastic interaction analysis, and for times greater than zero, approximate results can be obtained from elastic interaction analysis using

$$K_s = \frac{E_i}{(1-v_i^2)J(t)}$$

Errors in these approximate results are zero at $at = 0$, and with increasing time the errors increase to a maximum value and then decrease. The magnitude of the errors increases with increasing β . When $\beta = 1$, the maximum errors in eaves moment, outer column load and differential settlement are 2%, 1% and 4% respectively, while for $\beta = 2$ the corresponding maximum errors are 3%, 1½% and 6%.

EXTENSION OF RESULTS

While the results which have been presented correspond to single values of certain parameters, the effects of changes in various parameters may be predicted on the basis of elastic interaction analyses (Brown, 1975). That such predictions will be reliable, follows from the fact that the present results vary comparatively little from elastic interaction results, as indicated in the previous section.

Changes in the length/breadth ratio of the footing, changes in the column stiffness/beam stiffness ratio and changes in the number of storeys in the building, have little effect on interaction results when these are presented in terms of the relative stiffnesses previously defined.

An increase in the number of bays in the frame has little effect on column loads or eaves moment, but will cause some increase in differential settlement ratio. When a structure has only two bays, the distribution of column loads may be quite close to that required for zero differential settlement, and consequently a small change in the structure could have a proportionally large effect on the interaction behaviour. For two-bay frames, eaves moment ratios may be appreciably higher than for three-bay frames, however it will be conservative to assume that differential settlement ratio and outer column load ratio are unaffected by the reduction in number of bays.

An increase in the fraction of the footing covered by the building from 0.90 (as in the example presented) to 0.98 will cause some decrease in differential settlement ratio, eaves moment ratio and outer column load ratio (Brown, 1975). Thus the results presented will usually be conservative, since most buildings cover at least 90% of the length of their foundation.

Different rates of Creep, that is different values of β , have little effect on results when these are plotted against

$$T = \frac{\beta \ln(1+at)}{1+\beta \ln(1+at)}$$

instead of against at .

Thus if a result is required at time τ for $\beta = c$, a close approximation can be obtained by entering the graphs at $at = (1+c\tau)^C - 1$.

CONCLUSIONS

Solutions for interaction of a typical building-footing system with a soil subject to creep are presented for a wide range of relative stiffnesses.

It is also shown that:

- (i) these results are largely unaffected by changes in the building-footing system, unless the number of bays or the fraction of the footing covered by the building is changed, and in such cases the effects are discussed.
- (ii) these results may be obtained to satisfactory accuracy by appropriate elastic interaction analyses, when the creep rate is moderate.
- (iii) results for rates of creep other than the adopted, can be approximately predicted by a simple method.

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